DEPARTMENT OF THE ARMY CORPS OF ENGINEERS

BEACH EROSION BOARD
OFFICE OF THE CHIEF OF ENGINEERS

THE ACCURACY OF PRESENT WAVE FORECASTING METHODS WITH REFERENCE TO PROBLEMS IN BEACH EROSION ON THE NEW JERSEY AND LONG ISLAND COASTS

TECHNICAL MEMORANDUM NO. 24

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By WILLARD J. PIERSON, JR.

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THE ACCURACY OF PRESENT WAVE FORECASTING METHODS

WITH REFERENCE TO PROBLEMS IN BEACH EROSION ON

THE NEW JERSEY AND LONG ISLAND COASTS

ABSTRACT

Detailed weather data and wave data for every four hours were obtained from 22 April 1948 to 31 May 1948. An attempt was made to fit the observed significant height and significant period to the forecasted significant height and significant period within the range of accuracy of the weather data. It was, in general, possible to obtain good agreement between the observed and forecasted significant heights.

Various examples of the techniques employed are described. In particular, an east coast storm and a tropical hurricane are studied. The data were tabulated with reference to single valued versus multiple valued forecasts, and with reference to accepted wave forecasting methods, and, as yet, theoretically unjustified extensions. Since good height agreement was obtained by a deliberate choice of forecast parameters within the range of their possible values, only the accuracy of the period forecast is discussed.

A statistical study of the results obtained shows that the forecasted significant periods, no matter what the method, are not accurate and that they are not distributed according to the distribution of the observed significant periods. More accurate forecasts would have been obtained by making a simple climatological forecast, that is, by forecasting the average value of all observed significant periods in all cases. Table 10 summarizes the statistical results which were obtained.

An attempt is made to verify the refraction diagram for Long Branch, New Jersey. It is shown that the forecasted values for deep water were so inaccurate that verification of the diagram is not possible.

The data are sufficiently accurate, however, to permit the qualitative discussion of problems connected with beach erosion. The direction of the littoral current for various deep water wave directions is discussed both for waves from a distance and for local waves. Some of the effects of an east coast storm on the shore line are described, and the statistical properties of east coast storms are given.

It is concluded that hindcasts which are made in order to obtain statistical data about waves at a given location may not be accurate enough to be worth the effort involved.

In addition, any problem in wave action which depends critically upon the wave period cannot be accurately handled by the present forecasting methods.

Section 1 - Formulation of Problem

The problem investigated in this study can be formulated as follows. Given wave records taken every four hours at Long Branch, New Jersey from 4 pm 22 April 1948 to 12 midnight 31 May 1948, and given all available weather information for the above period, apply the wave forecasting techniques developed by Sverdrup, Munk (16,17), and Arthur (1, 2) to the weather and compare the forecasted values with the observed values in order to determine if the forecasted techniques work and if the forecasted values of wave height, period and direction can replace the observed values in problems connected with beach erosion. Thus this study is not an attempt to forecast the waves; to the contrary, it is an attempt to determine whether or not the forecasting techniques can yield the observed values of the wave parameters given the choices possible in picking the forecasting parameters due to the limitations of the available data. Every effort was made to get the observed and forecasted values to agree, and therefore the lack of agreement which will be demonstrated is in a large part the consequence of a failure of the forecasting method.

Section 2 - Data Employed

In order to carry out this wave forecasting study, weather data, refraction data for Long Branch, and wave records at Long Branch were obtained. The weather data were most comprehensive and represented the best possible weather coverage of the Atlantic Ocean and of the east coast of the United States near Long Branch. The refraction data consisted of the values which were obtained by Pierson (14) in a previous report. The wave records were obtained by the Beach Erosion Board.

The weather data consisted in part of six hourly weather maps which included the eastern edge of the United States and the Atlantic Ocean within a radius of several thousand nautical miles of Long Branch. Two different analyses of the weather data were employed. One set of weather maps was obtained from the North Atlantic Analysis Section at La Guardia Field through the courtesy and cooperation of the Weather Bureau. The second set of weather maps was obtained from the Search and Rescue Section of the United States Coast Guard through the courtesy and cooperation of the Coast Guard. Thus two maps for each observation period were available. Since the analysis of weather maps in part depends on the subjective application of various analysis techniques, the two analyses varied slightly for the same weather data and the two maps were compared in order to obtain the best wave forecasts.

In addition, the weather data consisted of airway observations at La Guardia Field, Floyd Bennett Field, Atlantic City, and Lakehurst Naval Air Station. These observations at each station were usually made hourly, but if the weather was changing rapidly, they were made more frequently. The winds reported in the airway observations were accurate to within one mile per hour and they proved to be most helpful in forecasting waves due to winds near the coast.

The wave records were obtained at Long Branch, New Jersey, by the Beach Erosion Board. The recording instrument was a step resistance gage developed by the Beach Erosion Board (4). The true height of the water surface as a function of time was recorded. It is important to point out that low period waves would not have been filtered out by the process of recording because the instrument was not a pressure-type recorder. The wave recorder was operated every four hours for seven minutes. A discussion of the analysis of the wave data will be postponed until the next section.

The refraction data was obtained by the orthogonal method after a study of the techniques described by Sverdrup and Munk (18), and Johnson, O'Brien and Isaacs (11). Figure 1 gives the refraction diagram for waves with periods from three seconds to fourteen seconds. The theory of wave refraction is based upon the assumption that the waves are purely periodic. A discussion of this phase of the study is given by Pierson (14). Some conclusions as to the accuracy of Figure 1 are possible as a result of this study of forecast methods, and they are given in section 8.

Section 3 - Analysis of Wave Records

The wave records were recorded on Brush Recorder Rolls. The Beach Erosion Board analyzed the records for significant height and period and furnished both their analysis and the original records for the study.

The definition of significant waves as given by Sverdrup and Munk (17) is based upon a statistical analysis of the wave records. Significant waves are defined as waves having the "average height and period of the one third highest waves." The above definition at first appears to be precise, but in reality the analysis of wave records according to the above definition is subject to considerable subjective interpretation on the part of the analyst. Also the definition itself is sometimes inconsistant and leads to contradictory results in the evaluation of other wave parameters.

WAVE REFRACTION AND SHOALING
AT LONG BRANCH, NEW JERSEY
FOR MEAN SEA LEVEL
(NEGLECTING FRICTION)

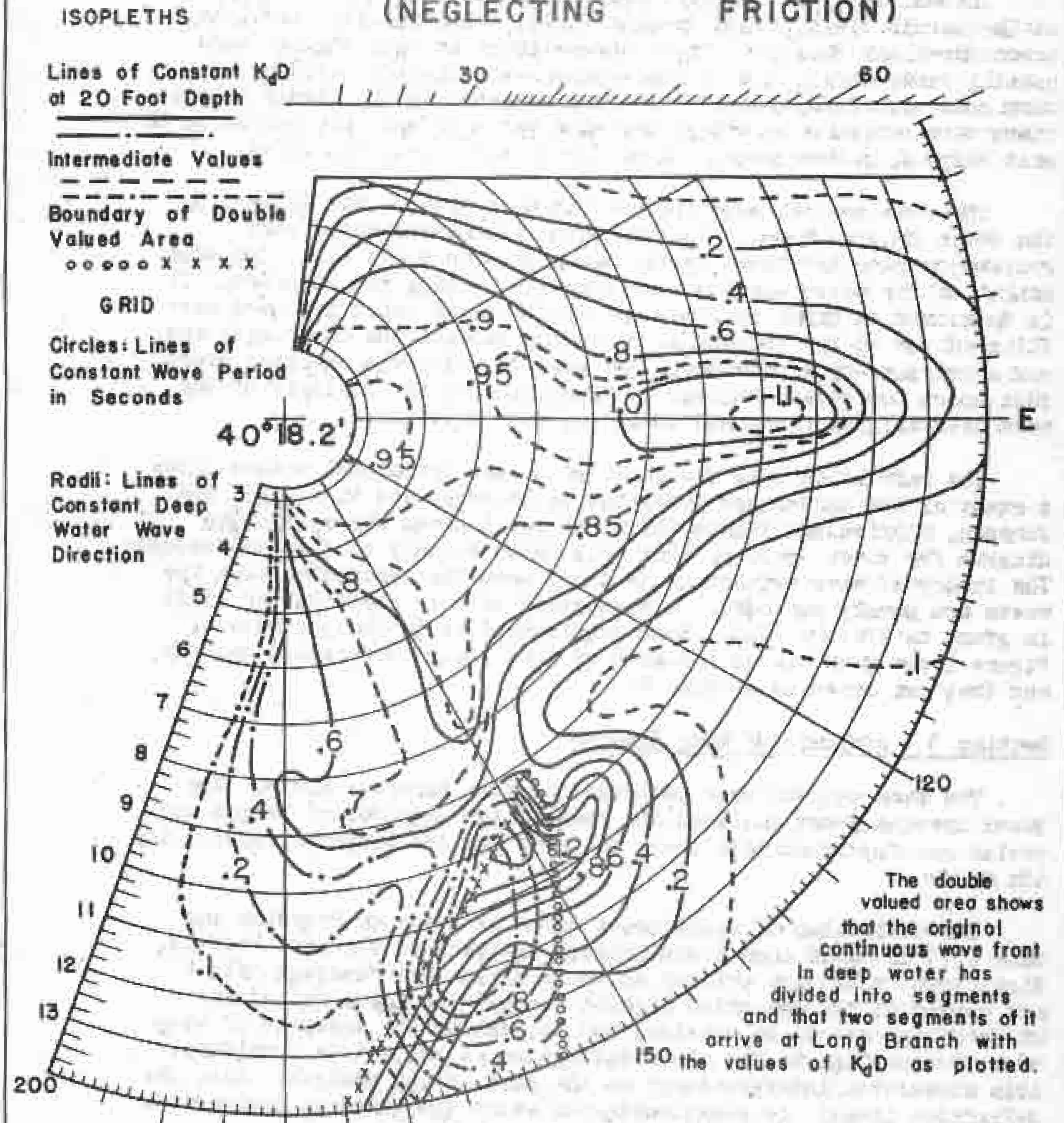
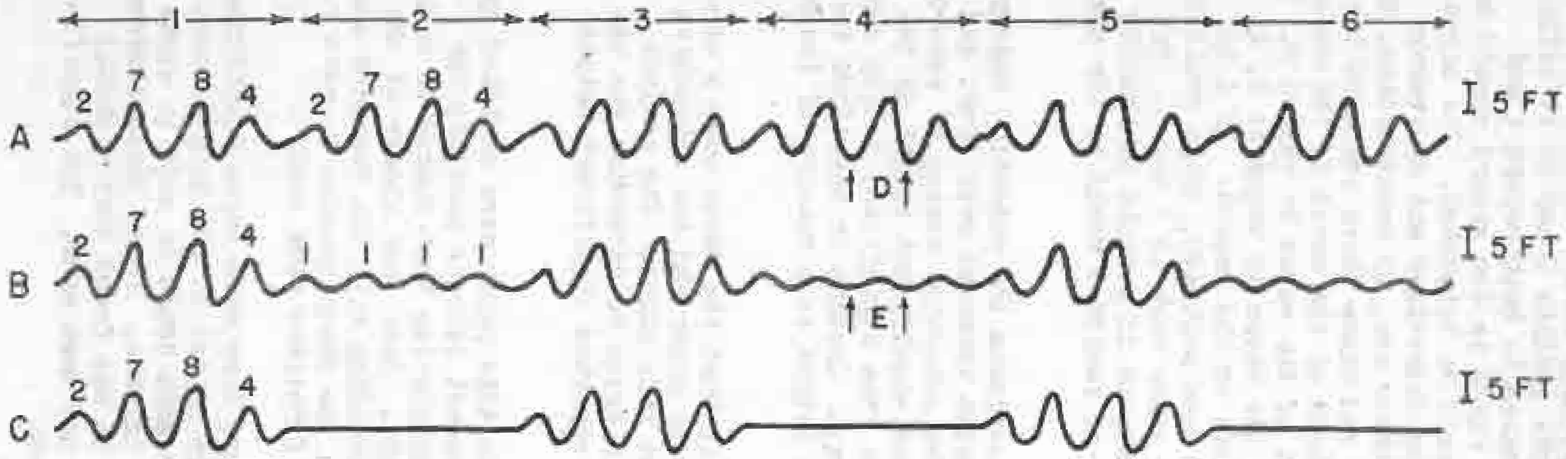


FIGURE I



A

HT	FREQ.
8	6
7	6
4	6
2	6

SIGNIFICANT HEIGHT
7.75 FT

B

HT	FREQ.
8	3
7	3
4	3
2	3
1	12

SIGNIFICANT HEIGHT
6.63 FT

C

HT	FREQ.
8	3
7	3
4	3
2	3

SIGNIFICANT HEIGHT
7.75 FT

FIG. 2 HYPOTHETICAL WAVE RECORDS TO ILLUSTRATE AN INCONSISTENCY IN THE CONCEPT OF SIGNIFICANT HEIGHT

Consider, for example, the three hypothetical wave records in Figure 2. First, a decision as to what is a wave must be made. If the occurrence of two successive troughs (points D and E) is called a wave, there are the same number of waves in both record A and record B. Then theoretically all the waves in the record should be counted and the height of each one should be tabulated. The highest one third of the heights should then be determined and an average taken of those height values. Since there are, by construction, the same number of waves in both records, and since there are more low waves in record B, the significant height of the waves in the record B is lower than the significant height of the waves in record A. Now consider record C. It might arise if the waves in segments 2, 4, and 6 of record B were too low to be visible on the record. If C is analyzed in the same way that A and B were analyzed, there would be only half the number of waves in C as there were in A and B. But also the percentage distribution of heights in C would be exactly that of A, and the significant height of record C would be the same as record A.

The wave records can be used to evaluate the potential energy of the sea surface disturbance at a point averaged over time, and it can be seen from the figure that the potential energy of record C is half of that of record A. Since the significant height is the same in both cases, it is evident that the significant height cannot be used to compute the potential energy. Caution is therefore indicated on the use of the significant height as a measure of incoming wave energy in theoretical work.

Records which approach record C in that the waves over a considerable time interval are quite low do occur and the subjective interpretation of the record enters at this point. The analyst does not count all of the low waves in order to determine the one third highest, and so in general the reported significant height is too high.

The significant waves reported in this paper were analyzed by counting the total number of waves present (except possibly the very low waves), dividing by three, tabulating that number of high waves, and computing the average height. Some spot checks of the reported heights were made before proceeding with the forecast study and the spot check values agreed with the Beach Erosion Board's values so the height data which they furnished were used.

As the forecasts were carried out, they were three significant height observations which could not be fitted to the height forecasts whereas usually the height forecasts could be made to agree quite successfully with the observed heights. These three observations were checked, and in each case it was found that probably some computation or tabulation error had been made. The significant heights were corrected as follows:

TABLE 1. CORRECTED SIGNIFICANT HEIGHTS

Date	Time	Value	Corrected Value
29 Apr	9 p.m. E.D.T.	5.53 ft.	2.20 ft.
8 May	12 noon E.D.T.	4.54 ft.	2.86 ft.
8 May	4 p.m. E.D.T.	7.14 ft.	3.37 ft.

The analysis of wave periods seems to be subject to even more subjective interpretation on the part of the analyst. Some records will be discussed in section 7 which show two periods superimposed as in curve A of Figure 3 and it will also be shown that frequently several wave trains can be forecast to arrive simultaneously and that the superimposed periods cannot be separated by analysis.

Even when the weather situation shows that only one wave train should arrive at Long Branch, some of the wave records are difficult to analyze because of their extreme irregularity. Consider for example the remaining two hypothetical wave records in Figure 3. Curve B presents one type of problem. Are the small irregularities at (1), (2) and (3) to be considered as waves or is the major trend represented by (5) to be considered a wave? If (1), (2) and (3) are averaged with (4) and (6), a low value for the period results. If the small irregularities are ignored and (5) is averaged with (4) and (6), a high value for the period results. Finally if only (4) and (6) are considered, a moderate value of the period results. And as soon as rules governing such situations are defined, something like (7) occurs, and the rules fail to work.

In record C, the high waves have shorter periods and the low waves have longer periods. If (1) and (2) are averaged, one value is obtained; if the low waves are among the third highest, and if (3) and (4) are averaged with (1) and (2) a different value is obtained.

As the test forecasts proceeded, it became evident that the significant periods were not being forecasted accurately. So the wave records were re-analyzed for values of the significant period. A few records like record A were detected. Records like record B were encountered most frequently. In the independent re-analysis, the ten highest most "wave-like" waves in the record such as (4) and (6) in B were selected and their periods were measured. The average of the ten was called the wave project significant period. The values obtained are graphed in section 7 along with those tabulated by the Beach Erosion Board. It is not claimed that the re-analyzed values are more accurate. The re-analysis was made with the hope that the forecasts for the period would verify better with the new values.

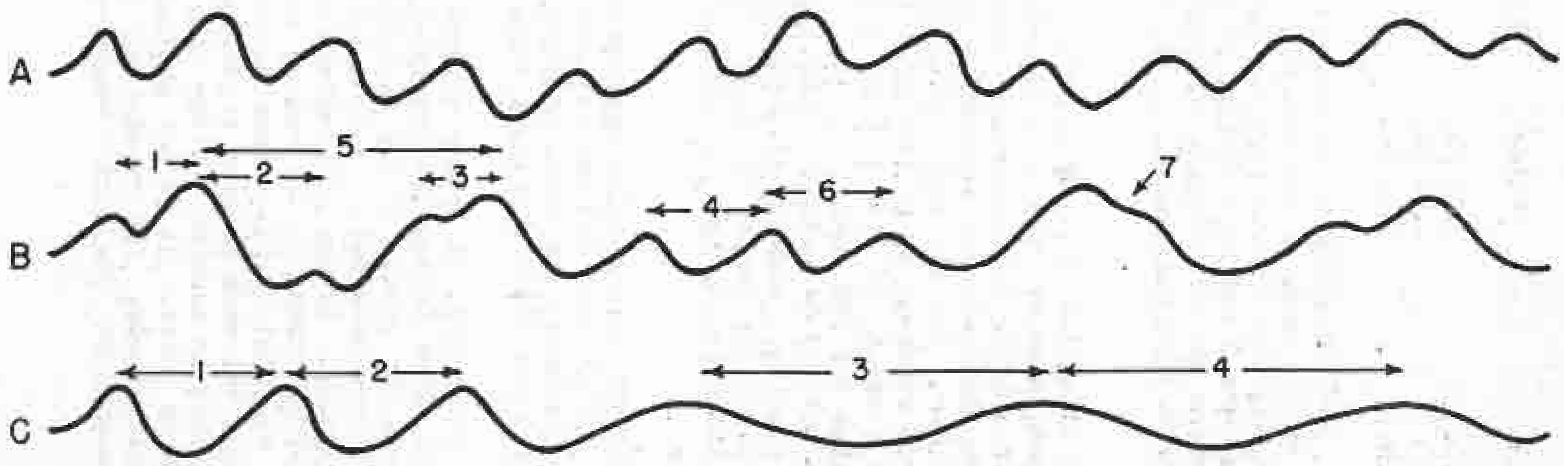


FIG. 3 HYPOTHETICAL WAVE RECORDS TO ILLUSTRATE THE DIFFICULTY IN EVALUATING THE SIGNIFICANT PERIOD

Section 4 - Sources of Error in Data

The weather data, the wave data, and the refraction data are all indefinite to a certain extent. They are measured or computed values and hence they can be in error. In addition, the weather data, by the way in which it is reported, can lead to errors in the wave forecasts.

The sources of error in the wave data analysis have already been pointed out. The sources of error in the refraction diagram were in part discussed by Pierson (14).

In addition to the sources of error in the refraction diagram, errors in the forecast values due to refraction could also enter because of inaccurate values of the deep water wave direction or because of inaccurate values of the period. The errors which enter because of inaccurate deep water wave direction can be minimized and the error due to incorrect periods can be evaluated to a certain extent. The methods of accomplishing the above are discussed in section 5 and section 8.

By far the greatest source of wave forecast errors lies in the nature of the six hourly weather maps. To obtain a forecast, a fetch must be determined; the wind direction, speed, and duration must be evaluated before the forecasting graphs are employed. In the forecasting method it is assumed that effectively the wind starts blowing at an instant of time and blows at a constant velocity for so many hours and stops instantaneously. Various empirical rules have been put forward for averaging variable velocities to get the single velocity value needed for the forecast (see Arthur (2)). Effectively the rules weight the high velocities more than the low velocities.

The present six hourly weather maps permit a range of choices in determining the needed parameters for the forecast. The direction of the winds over the fetch is reported to only 16 points of the compass, the winds are reported in the Beaufort Scale (see Berry, Bollay, Beers (5)) with a range of possible velocities for each code symbol, and the duration of the winds is of course indeterminate to within six hours at both the start and the stop of the winds.

For example, suppose that four successive weather maps report northeast winds of strength Beaufort six over the given area of the ocean, and that the weather maps both before and after show light winds over the same area. The direction of the winds can be any value from 34^o east of north to 57^o east of north. The wind velocity can be any value from 22 knots to 27 knots. The duration can range from twenty four hours to close to thirty six hours depending on the time chosen for the starting of the winds before the first of the four maps and the stopping of the winds after the last of the four maps. The range of values possible in the forecasted height, period, and direction is therefore very large.

Frequently it is possible to restrict the range of the above mentioned values by other considerations. A check of the movement of a storm center can determine the duration more accurately. If half of the ships in the area report Beaufort 6 and half report Beaufort 7, then a better estimate of the wind speed is 27-28 knots. If the fetch terminates against the coast, the hourly observations of coastal stations fix the duration to within an hour or so and the veloctiy to within a knot.

Considerable attention is given by Sverdrup and Munk (17), Arthur (2) and Emmons (7), to the problem of the computations of the winds over a fetch from the isobar spacing and the geostrophic wind. This problem was not encountered in this study because the ship reports were usually dense enough to obtain the wind velocities directly within the accuracy of the Beaufort Scale. In addition in the developing east coast storm the non-geostrophic wind components appeared to be so large that computations based upon geostrophic winds would have been highly doubtful.

All of the above sources of error were minimized to a large extent by the techniques used in the preparation of the test forecasts. However, there is one remaining basic inconsistency between the forecast methods and the actual weather situation. It is that the wind field varies continuously in time and space (except possibly at shear lines and fronts) and many times it seemed to be a highly artificial procedure to split up the wind field into arbitrary generation and decay areas and to decide upon constant wind speeds and definite durations.

Section 5 - Forecasting Methods Employed

The usual forecast techniques as described by Sverdrup and Munk (17) and Arthur (2), were employed in the preparation of the test forecasts. The paper by Arthur (1) on the variability of wave direction proved to be most helpful. In addition, two types of weather situations arose frequently in which the techniques given by the above authors did not seem applicable, and two new unproved methods were adopted for forecasts for these situations.

The forecasting charts that were used for the test forecasts are found in "Revised Wave Forecasting Graphs and Procedure" by Arthur (2). Plates I, II, III, IV, and V were used. The procedures described for following and opposing winds were used whenever applicable.

The paper entitled "Variability in Direction of Wave Travel" by Arthur in combination with the refraction diagram given in Figure 1 made it possible to explain the occurrence of many waves which otherwise could not have been forecast*. Reference to the

*See also the comments by Donn in the same reference and the paper by Donn (6) in the A.G.U.

refraction diagram shows that waves with periods from 8 through 10 seconds (for example) are strongly attenuated by refraction unless they approach from due east or from an azimuth of 150°. In addition without Arthur's results local winds from the south south west would not be expected to produce very high waves at Long Branch.

Arthur's conclusions and the alignment chart which he gives (Figure 4 of reference 1) make it possible to maximize the forecasted wave height by bringing the waves in from a deep water direction of either due east or from an azimuth of 150° for the whole range of possible wind directions from east north east to south south west if the fetch terminates against the coast. Thus if the forecast period is high enough to yield very low values of K_dD for say waves from the southeast, it is possible to bring the waves out of the fetch at an angle of forty-five degrees (with a reduction of only 10% or so in the period and 40 to 50% in the height) and use the refraction value for waves from due east. Low period local wind waves from south winds can also be brought in at an angle of 30° to the fetch and the attenuating effect of refraction thus minimized.

For distant fetches, of course, such freedom does not exist, but Arthur's results permit the determination of many distant fetches which otherwise could not be used to forecast the arrival of waves at Long Branch. For example, strong northeast winds in the area north of a line running due east of the southern tip of Cape Cod occurred frequently. Were the waves to travel in the direction of the winds, they could not reach Long Branch, but if the fetch penetrated a little to the south of Cape Cod, it would then be possible to bring the waves out of the fetch at an angle of 45° and bring them in to Long Branch from due east. The above considerations frequently explained waves which could not have been explained in any other way. The application of the variability in the direction of wave travel to specific cases will be discussed when the forecasts are discussed.

In addition to the standard techniques just described, two new procedures had to be employed in order to explain waves which could not be explained by previously known methods. The two procedures were adapted to account for the decay of waves in the fetch and to account for the effects of turning and increasing winds in close-by rapidly moving east coast storms.

One weather situation which occurred quite frequently might be described by the following example. Suppose that there were east winds off the coast of New Jersey extending over the Atlantic to distances of the order of five hundred nautical miles. Suppose that the east winds last for say, thirty hours, and then die out suddenly. The usual methods permit forecasts of the waves up to the time that the wind stops blowing, but just after the wind stops, the ocean out to distances of five hundred nautical miles is covered with waves traveling toward shore. Now, the Sverdrup-Munk theory states that, except for the last eighty or so miles of the fetch, the same significant waves will be found over the entire fetch, but it does not tell us what waves will be observed at the end of a fetch several hours after the winds over the fetch have ceased. In the above situation, it is expected however, that waves will continue to be observed for quite a while after the winds have ceased.

It should also be noted that the entire theory of the decay of waves is based upon the values of the significant height and period at the end of the fetch. A situation exists therefore in which the present theory is not applicable. For the prepatation of the test forecasts for this paper, the significant waves at various distances from the shore were decayed that distance to the shore. The area was treated as if the original fetch had terminated at say, fifty miles from the coast, and a forecast for the waves, say, four or five hours after the winds had stopped was obtained. Then the waves one hundred miles from the coast were decayed that distance to the shore and a forecast for the waves eight or ten hours after the winds had stopped was obtained. By exhausting the entire fetch (with proper regard to the fact that the length of the fetch and not the duration of the wind was the limiting factor at the far end) it was possible to obtain forecasts for waves which could not otherwise have been forecast.

The decay in fetch method has been used on the west coast as a general procedure when situations similar to the one described above arose. The method will be described in a forthcoming publication by the Hydraographic Office. The "decay in fetch" procedure has apparently not been justified theoretically. An example in which it was used is given in the following section, and a statistical analysis of the results obtained by its use is given in section 7.

Finally, during the passage of an east coast storm, the winds might be southeast 20 knots for 15 hours, then east south east 27 knots for 9 hours, and then east 39 knots for 4 hours. The usual procedures for averaging did not seem to be appropriate and so a method was developed which gave good results for the heights but which led to inconsistencies in the period. The method for accounting for turning and increasing winds will be described when the forecasts for an east coast storm are analyzed.

Section 6 - Forecast Technique and Some Examples

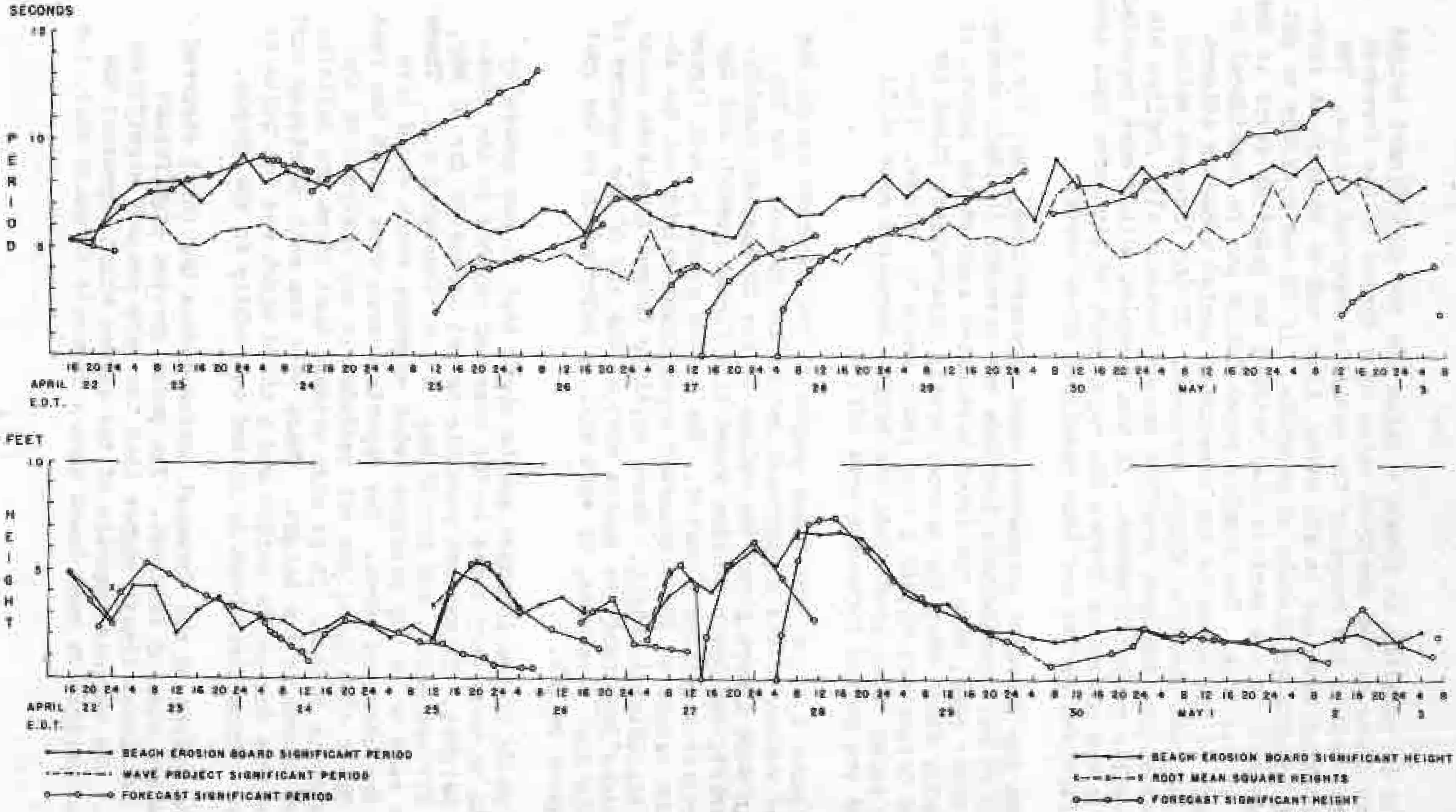
As the test forecasts were attempted it soon became evident that it was extremely difficult to hit the period forecasts. Or, to put it another way, to obtain values near the observed significant period would require the use of winds outside of the possible range of the reported values or would result in tremendous discrepancies in the reported heights. On the other hand, it usually seemed to be possible to obtain a value for the significant height which was close to the observed value by a choice of the forecast parameters within the range of the possible reported values. The procedure that was used in all cases, then, was to attempt to forecast the heights as closely as possible. If it was possible to get good agreement in the periods also without too great an error in the height, it was done. The results which follow can be considered to be a study of the error in the forecasted period after an attempt to get the best possible height forecast. If the forecast method works perfectly, the best possible height forecast also implies the best possible period forecast. If the forecast method work imperfectly, the above procedure throws the major part of the error into errors in the forecast period and thus magnifies those errors.

When the forecast parameters were indeterminate, say, for a distance storm, considerable latitude was possible in their choice. On the other hand, when the fetch terminated against the coast, it was usually found that the coastal hourly observations fixed for forecast parameters within a very small range of values. Frequently under these conditions the height forecasts were still good and the period forecasts were off.

Figures 4, 5, 6, and 7 are graphs of the forecast versus the observed values of the significant height and period. The top graph in each figure gives the values of the forecasted significant period, the Beach Erosion Board significant period, and the wave project significant period. The bottom graph in each figure gives the values of the forecasted significant height and the observed significant height. Where multiple height forecasts occur the crosses represent the square root of the sum of the squares of the individual forecasts, or what will be referred to as the root mean square height.

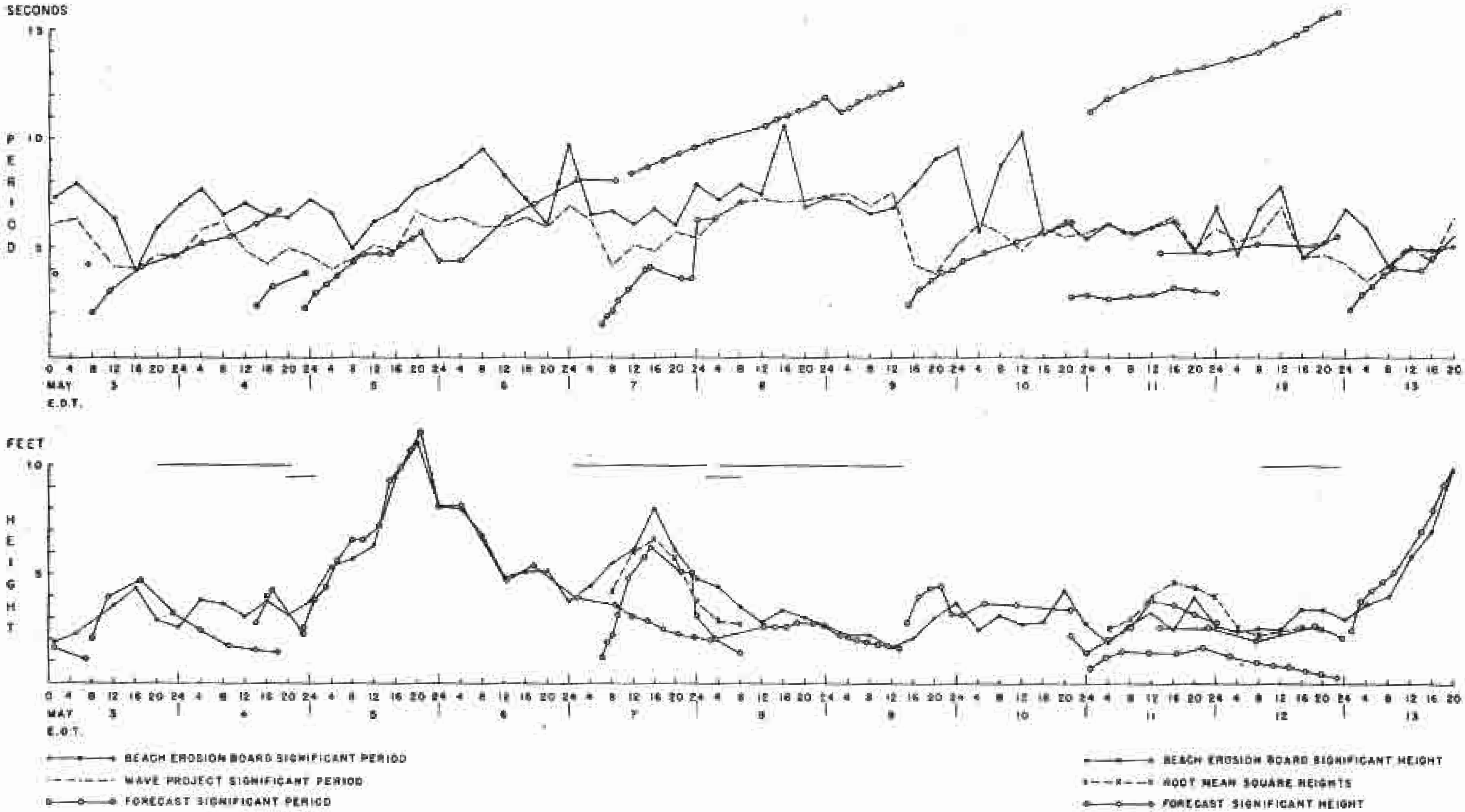
A study of the forecast graphs shows that it was generally possible to come very close to the observed heights in the forecasted heights. It was not possible to get forecasts for 20 May, 4 a.m. through 8 p.m. and for 22 May, 8 a.m. through 8 p.m. There did not seem to be any possible fetch anywhere which would have caused the observed waves. The reported waves were about two feet high. These nine cases are not included in any analysis of the results which follow. It is also evident that there are definite forecast trends in the height. There were two well developed east coast storms during the period and a third which was not quite so intense. These storms can be picked out easily on the graphs.

The graphs of the forecast period versus the (two) observed periods are also of interest. The Beach Erosion significant period is almost always higher than the wave project significant period. The various segments of the curves which represent the forecast period are each based upon a separate forecast unit, i.e.



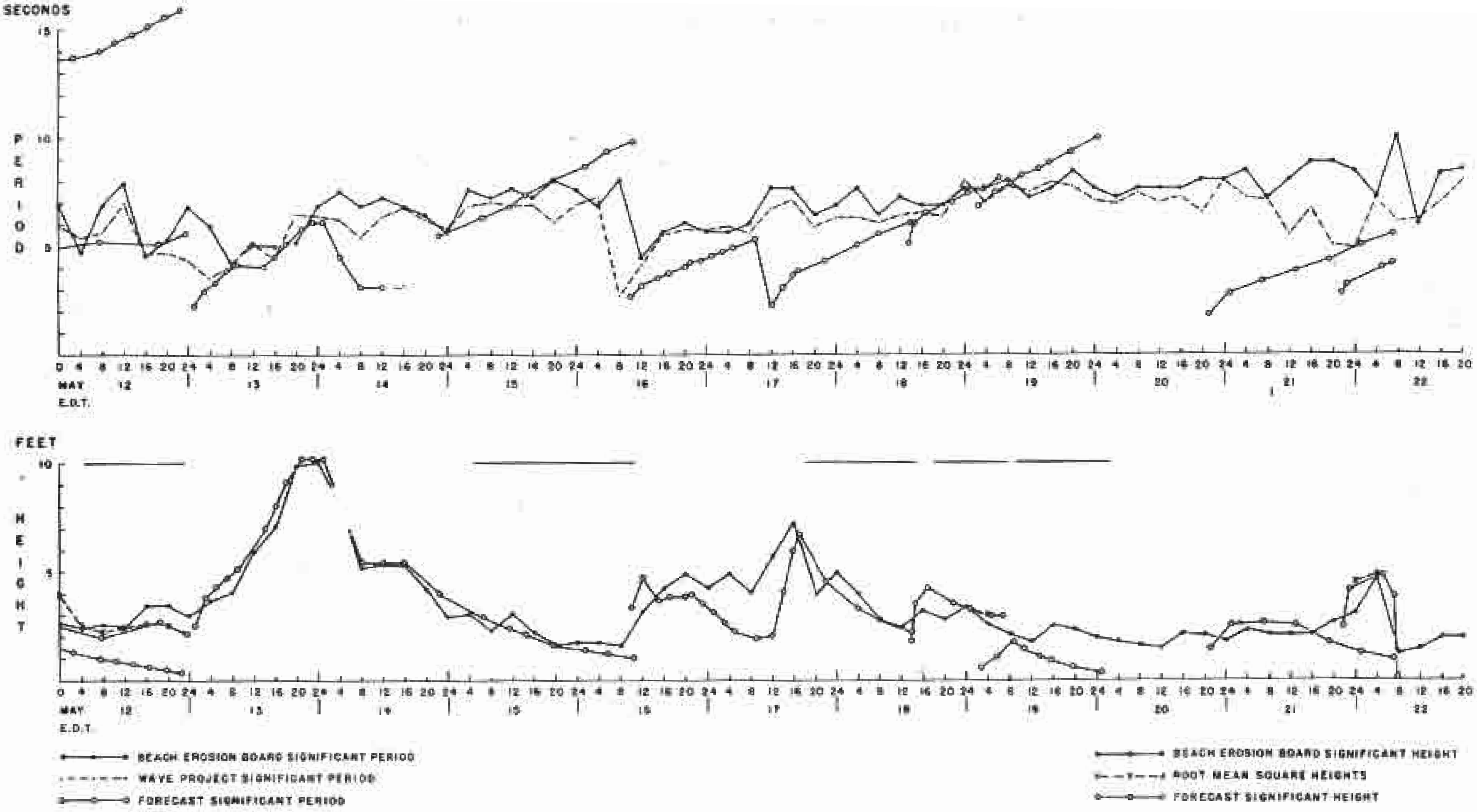
GRAPHS OF FORECAST AND OBSERVED WAVE PARAMETERS

FIG. 4



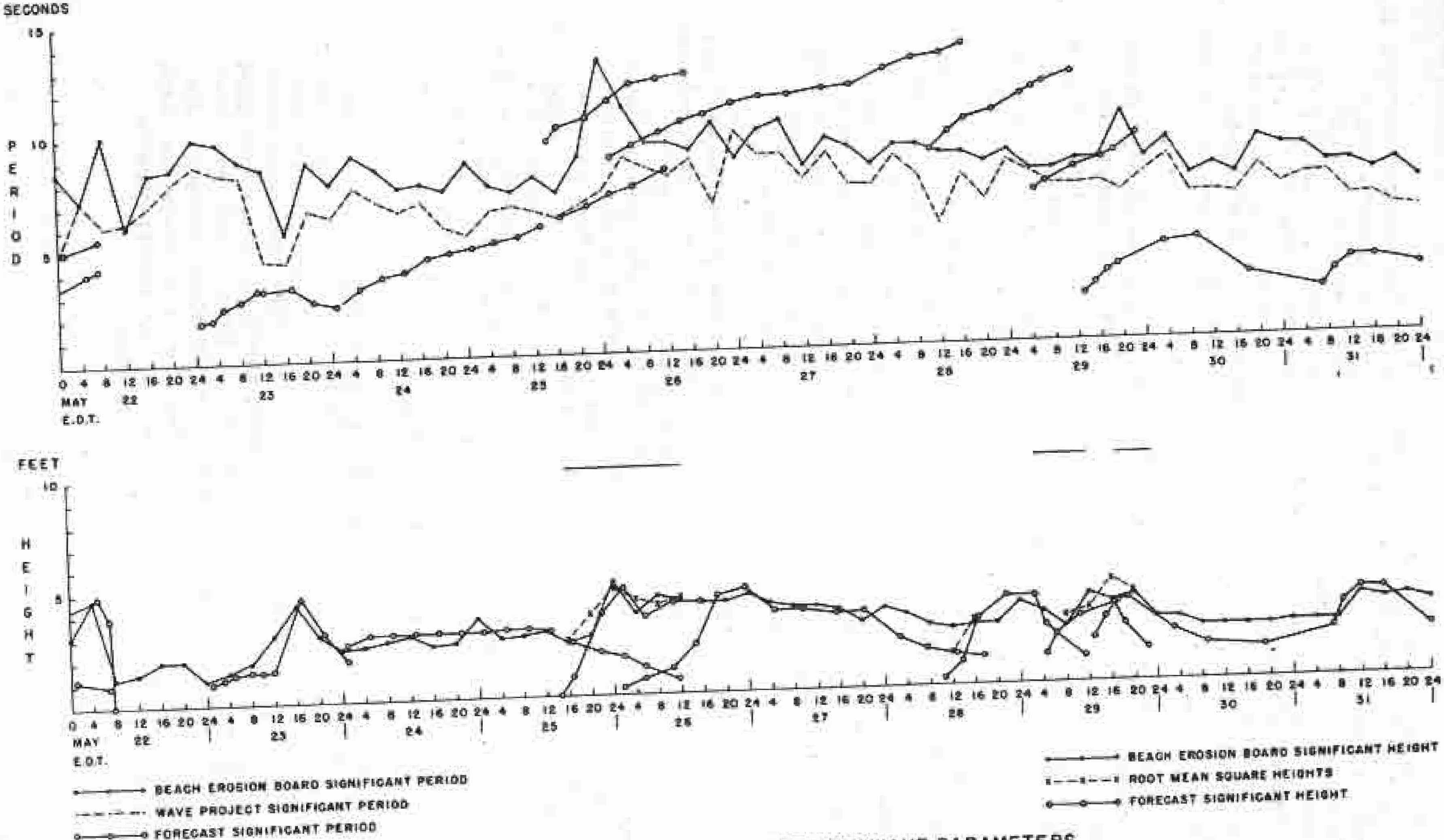
GRAPHS OF FORECAST AND OBSERVED WAVE PARAMETERS

FIG. 5



GRAPHS OF FORECAST AND OBSERVED WAVE PARAMETERS

FIG. 6



GRAPHS OF FORECAST AND OBSERVED WAVE PARAMETERS

FIG. 7

a distant fetch and the other forecast parameters associated with it. Each segment is usually a continuously increasing curve which terminates when the forecast heights become too low to amount to anything or possibly when the fetch is exhausted in the case of a situation in which decay in the fetch was used. One difficulty in the present forecasting methods seems to be that once the process of forecasting for a given fetch is started it becomes almost impossible to forecast non-increasing or decreasing periods if the fetch is fairly long.

The trend in the observed value should also be noted. There are definite trends in the heights which sometimes persist for several days, and it was usually possible to see how they could be associated with the major meteorological changes. The trends in the observed periods are much less pronounced and the values seem to fluctuate much more rapidly from one observation to the next.

Finally it should be mentioned that six observations per day are reported. The observed values are therefore dense in time, and it is possible to study the build-up of waves in the fetch and other points of interest. Less frequent observations, say, twice a day, would have made the problem of testing the forecast methods much more difficult. Continuous recording of wave records such as reported by Isaacs and Saville (10) would have helped in determining the time of arrival of waves from a distant fetch.

The techniques employed in carrying out the forecasts will now be discussed by describing actual examples of the methods summarized in Section 5. The examples to be discussed in order are: (1) Example of the Decay of Waves in the Fetch, (2) Examples of Variability in Direction of Wave Travel, (3) Example of East Coast Storm, Turning and Increasing Winds and Associated Wave Records, (4) Example of a Hurricane and Associated Wave Records, (5) Examples of Superimposed Wave Forecasts and Associated Wave Records. The purpose in discussing these examples is threefold. First, the discussion shows how the forecast techniques are applied. Second, the new techniques described in Section 5 are of interest. Third, the discussion will in part help to substantiate some of the conclusions which are made in the following sections.

1. Example of the Decay of Waves in the Fetch. A well defined example of the occurrence of such a situation was found on April 27, 28, and 29 during the passage of a not-too-intense east coast storm as illustrated in Figure 4. The first saw tooth rise in wave height was caused by twenty-knot northeast winds from 0400 to 1000 on the 27th. The fetch (limited by Long Island) was short and the waves died out rapidly as soon as the winds stopped. The second saw-tooth rise in wave height was caused by twenty-two-knot south south east winds from 1400 to 2400 on the twenty-seventh. There was a lull from 0000 to 0400 on the 28th.

The 0130, April 28th, synoptic map shows a small low passing Hatteras with an open meteorological wave in it. The wave developed over the ocean and moved in such a way that it was possible to find a fetch with east south east winds about five hundred nautical miles long, terminating at Long Branch. The coastal wind reports combined with the synoptic maps indicated that the effective start of the winds would be 0400 EST and that the effective end of the winds would be 1500 EST. The coastal winds and the ship reports over the area indicated that the average wind velocity was 23 knots throughout the above time interval. The 1930 synoptic chart and the ones which followed it showed that the "low" had moved rapidly during the past six hours, that the winds over the part of the fetch nearest the coast were light and nearly perpendicular to the original winds over the fetch, and that no new fetch had been formed which could explain the observed waves after 1500 EST. Thus in order to forecast the waves at Long Branch up to 1500, the following table was prepared.

TABLE 2. BUILD UP OF WAVES FROM 0400 APRIL 28 TO 1500 APRIL 28. WIND 23 KNOTS DIRECTION ESE

Duration	H_f	Ref	H_r	Period	Time
1 hour	2.1	.98	2.1	2.2	0500 EST Apr 28
4 hours	5.8	.95	5.5	3.4	0800 EST
6 hours	7.9	.93	7.2	4.0	1000 EST
8 hours	8.0	.92	7.4	4.4	1200 EST
11 hours	8.3	.91	7.5	4.9	1500 EST

(Notation: H_f, Significant Height at End of Fetch, REF, Refraction Coefficient; and H_r Significant Height after Refraction)

The forecasted heights overshot the observed heights by about seven-tenths of a foot. The problem, though, is how to forecast the wave heights after 1500 EST. The decay in fetch method seemed to be the only possible way to forecast the waves after 1500 EST. Accordingly, it was assumed that waves with a height of 8.3 feet and a period of 4.9 seconds existed over the entire fetch except at the far end. Then the waves fifty nautical miles offshore were decayed that distance to the coast. By increasing the decay distance by fifty nautical miles increments, it was possible to forecast waves until April 30, 0200 EST. Table 3 shows the forecast parameters which had to be evaluated in carrying out the above procedure.

TABLE 3. EXAMPLE OF WAVE FORECAST BY THE DECAY IN FETCH METHOD

Waves 8.3 ft. high with a 4.9 second period over the fetch at 1500 April 28.

Decay Distance	H_D/H_F	Ref.	Travel Time	H_F	T_D	Time
50	.79	.92	6 hrs	6.0	5.4	2100 Apr 28
100	.60	.92	11 hrs	4.6	5.9	0200 Apr 29
150	.50	.93	16 hrs	3.8	6.3	0700
200	.42	.94	19 hrs	3.3	6.8	1000
250	.36	.94	24 hrs	2.8	7.2	1500
300	.32	.92	26 hrs	2.4	7.5	1700
350	.29	.86	29 hrs	2.1	8.0	2000
400	.26	.85	32 hrs	1.8	8.2	2300
450	.22	.80	35 hrs	1.4	8.6	0200 Apr 30

(Notation: H_D/H_F; Ratio of Significant height of waves after decay to significant height of waves at the end of the fetch; T_D, period of waves after decay. Other notation same as in Table 2)

Note that in Figure 4 and Table 4 the forecasted heights follow the observed heights throughout the entire period of the forecast. If either the Beach Erosion Board or the Wave Project significant periods are used as a check on the forecast periods, neither one agrees well with the forecast periods. The forecast periods lie between the spread of values of the observed periods. When the time of the forecast did not correspond to the time of the observation, the forecast values were interpolated linearly for the statistical analysis in Section 7. Table 4 gives the observed and forecasted values for the example discussed.

TABLE 4. OBSERVED AND FORECAST VALUES FOR THE EXAMPLE OF THE DECAY IN FETCH METHOD

Time	Observed BEB Sig. Period	Observed Wave Project Sig. Period	Forecast Sig. Period	Observed Sig. Height	Forecast Sig. Height
A 28 0800 EST	6.5	4.6	5.3	6.82	6.67 (RMS)*
1200 EST	6.6	4.7	4.4	6.76	7.4
1600 EST	7.4	4.4	5.0	6.86	7.25
2000 EST	7.5	5.4	5.3	6.55	6.25
2400 EST	8.4	5.7	5.7	5.52	5.20
A 29 0400 EST	7.4	5.7	6.1	3.97	4.30
0800 EST	8.2	5.5	6.5	3.51	3.63
1200 EST	7.5	6.2	7.0	3.50	3.10
1600 EST	7.4	5.5	7.4	2.56	2.60
2000 EST	7.5	5.6	8.0	2.20	2.10
2400 EST	7.7	5.2	8.3	2.22	1.67
A 30 0400 EST	6.4	5.4	8.3	1.94	1.27

*See Section 7 multiple valued forecasts.

If waves continue to come out of an area in which they have been generated after the winds have ceased over the area, then some additional theoretical investigation of their nature is needed. The above example shows one case in which a weather situation indicates that such considerations are the only possible way to explain some of the waves which occur in nature. In order to be consistent in this study every case in which a decay in fetch situation arose was treated in the same way as the one described above. In so doing, many waves were forecast which could not otherwise have been forecast and additional situations in which multiple forecasts arose were encountered. The lines over the height graphs in Figures 4, 5, 6, and 7 show those freecast values which were obtained by the decay in fetch method. The accuracy of the method will be discussed in the section which follows.

2. Examples of Variability in Direction of Wave Travel. An example in which the variability in direction of wave travel had to be considered was found on April 21, April 22, and April 23. On April 22, there had been northeasterly winds in the corner formed by Long Island and the New Jersey coast, but at about 1400 the winds died out rapidly and there were light winds incapable of raising the high waves which were observed. The values for the local waves are plotted for April 22, 1600 and 2000. East north easterly winds were also blowing in a band fifty to one hundred nautical miles wide to the south of Nantucket.

On April 21, 1930, the winds appeared to start with a force of Beaufort 5 and they lasted until April 22, 1930. On the next six hourly maps they had fallen off to a speed of 11 to 12 knots, and thereafter a high dominated the area and the winds were light. Figure 8 portrays the above facts pictorially. It also shows that the major wave train moves on past the area of interest, and that the way to forecast for Long Branch was to bring the waves out of the generating area at an angle of 30°. Table 5 shows the various forecast parameters which were evaluated in order to carry out the forecasts.

TABLE 5. EXAMPLE OF VARIABILITY IN DIRECTION OF WAVE TRAVEL Decay Distance 170 NM. Fetch 420 NM. Winds start at April 21, 1930. Wind speed 25 knots. Duration 18 hours.

Duration	H_F / T_F	$\theta = 30°$ H_θ/H_F / T_θ/T_F	H_θ / T_θ	H_D/H_θ / T_D	170 NM Decay Travel Time	Ref	Forecast H_r / T / Time
6 hrs	8	.87	7.0	.35	20 hrs	.96	2.35
	4.1	.95	3.9	5.9			5.9
							Apr 22 2130 EST
12 hrs	10.1	.84	8.5	.47	18 hrs	.98	3.90
	5.4	.96	5.1	6.8			6.8
							Apr 23 0130 E
18 hrs	11.8	.82	9.7	.55	17 hrs	1.00	5.3
	6.2	.96	5.9	7.5			7.5
							Apr 23 0630 E

(Notation: H_θ/H_F, Ratio of height of waves at θ^o to fetch to height of waves at 0^o to fetch. T_θ/T_F, Ratio of period of waves at θ^o to fetch to period of waves at 0^o to fetch. H_D/H_θ, Ratio of height of waves after decay to height of waves at θ^o to fetch. T_D, period of waves after decay).

In order to obtain forecasts after April 23, 0630, it was necessary to combine the theory of waves coming out of the fetch at an angle with the concept of decay in the fetch. The observed heights fluctuate considerably and the forecasts agree only near the peaks. The periods agree fairly well.

In addition to situations in which waves came out of a distant fetch at an angle, Arthur's results were useful for forecasting local waves. For example, on May 9 and May 10 there were twenty knot winds along the coast which were south south east from 1200 May 9 through 1600, May 9, south from 1600 May 9 through 2000, May 9, and south south west from 2000, May 9 through 2000, May 10. The eight hours of south south easterly winds and south winds were added to the duration of the south south westerly winds in the computation of the waves during the time that the south south westerly winds were blowing. The refraction diagram at Long Branch (Figure 1) shows that pure wave trains from the south south west would be strongly attenuated by refraction, but Figure 8 shows that the large scale orientation of the coast permits the generation of waves by south south westerly winds over the area of the ocean to the south of Long Branch. By bringing waves out of the generating area at an angle of 45^o, the effect of strong attenuation by refraction was minimized, and the forecast values graphed in Figure 5 were obtained. Table 6 shows the various parameters which were evaluated in order to carry out the forecasts. If the waves had been traveling only in a south south westerly direction, their height at Long Branch would have been less than eight tenths of a foot. In this case, the choice of either 30^o or 45^o would have been possible and essentially the same results would have been obtained in the heights because the increase in the values of H_θ/H_F would have been compensated for by a decrease in the refraction coefficient.

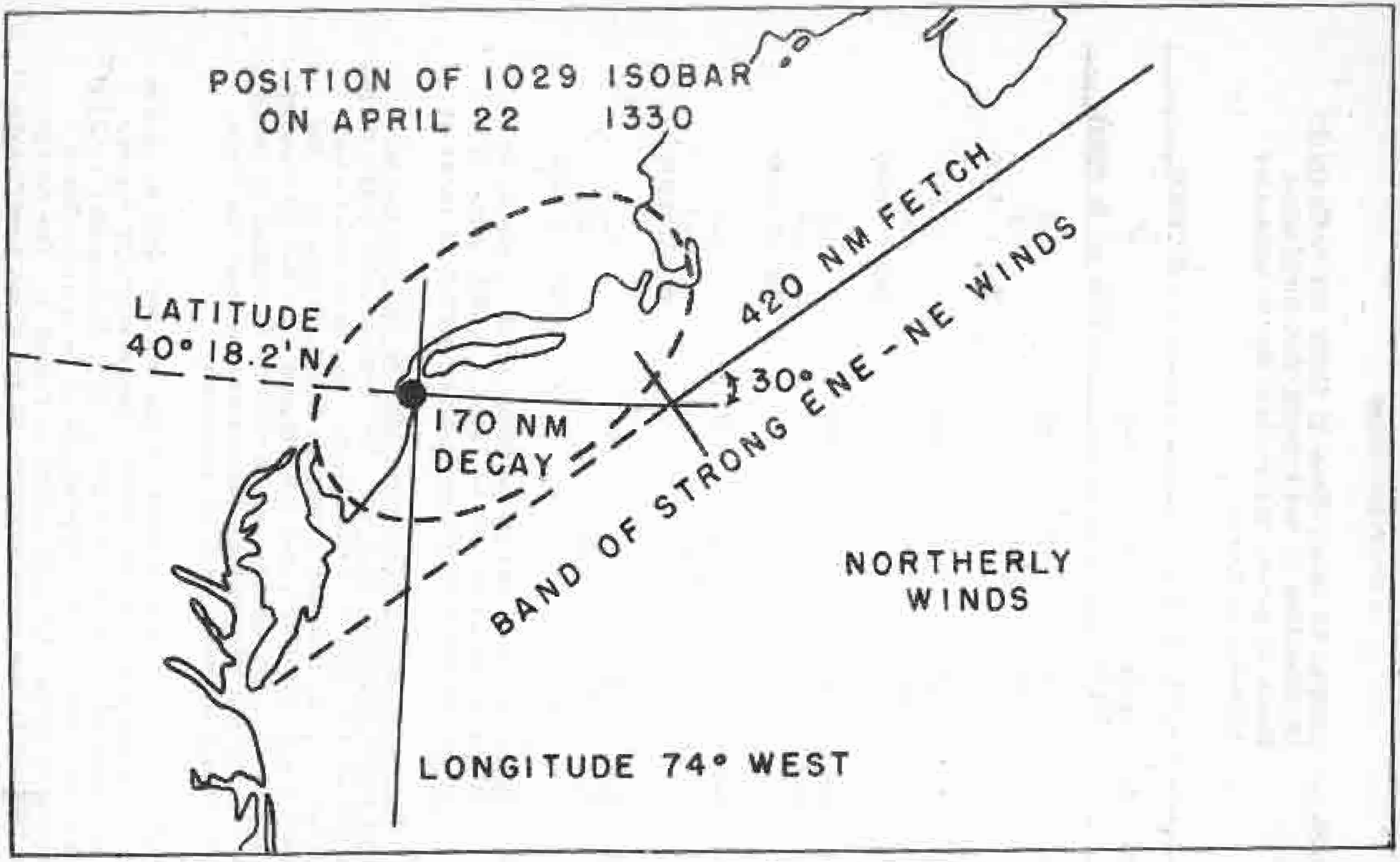


FIG. 8 EXAMPLE OF VARIABILITY IN DIRECTION OF WAVE TRAVEL

TABLE 6. EXAMPLE OF LOCAL WAVES IN WHICH THE VARIABILITY IN DIRECTION OF WAVE TRAVEL WAS CONSIDERED. Winds 20 knots, SSW at 2200 May 9, effective duration 10 hours.

	$\theta = 45^o$				Forecast
Duration	H_F / T_F	H_θ/H_F / T_θ/T_F	H / T	Ref	H^r / T^r / Time of Forecast
10 hours	6.3 / 4.4	.60 / .92	3.8 / 4.0	.85	3.2 / 4.0 / May 9 2200
12 hours	6.5 / 4.8	.59 / .91	3.8 / 4.4	.82	3.15 / 4.4 / May 9 2400
16 hours	8.0 / 5.3	.58 / .91	4.6 / 4.8	.80	3.7 / 4.8 / May 10 0400
22 hours	8.0 / 5.9	.57 / .90	4.6 / 5.3	.78	3.6 / 5.3 / May 10 1000
32 hours	8.5 / 6.9	.55 / .90	4.7 / 6.2	.72	3.4 / 6.2 / May 10 2000

(Notation: H_θ/H_F, Ratio of height of waves at θ^o to fetch to height of waves at 0^o to fetch. T_θ/T_F, Ratio of period of waves at θ^o to fetch to period of waves at 0^o to fetch.

3. Example of East Coast Storm, Turning and Increasing Winds, and Associated Wave Records. Two typical east coast storms occurred during the period of the study. One east coast storm affected Long Branch from May 4 through May 8 (Figure 5). The second east coast storm affected Long Branch from May 13 through May 16 (Figure 6). The earlier storm will be discussed in detail, and then some of the interesting differences between the first storm and the second storm will be described.

Figure 9 is a two page summary of the weather maps which are of interest in the study of the storm. Ten six-hourly weather maps of the area of interest from May 4, 0730 through May 6, 1330 are shown. The hourly wind observations at La Guardia Field during the same period are also given in Figure 9. The hourly winds at La Guardia are representative of the winds immediately offshore from New Jersey throughout the length of time considered (although sometimes when fronts are in the area they are not representative).

The map for May 4, 0730 EST shows light variable winds over the area of interst. The waves at Long Branch at that time were caused by minor winds which occurred on the third of May.

The map for May 4, 1330 EST shows that the storm of interst is just entering the western side of the map and that the warm front associated with the storm is about 150 miles south of Cape Hatteras. South south east nineteen knot winds were reported at La Guardia from May 4, 1100 E to May 4, 1600 E but they died out again after 1700.

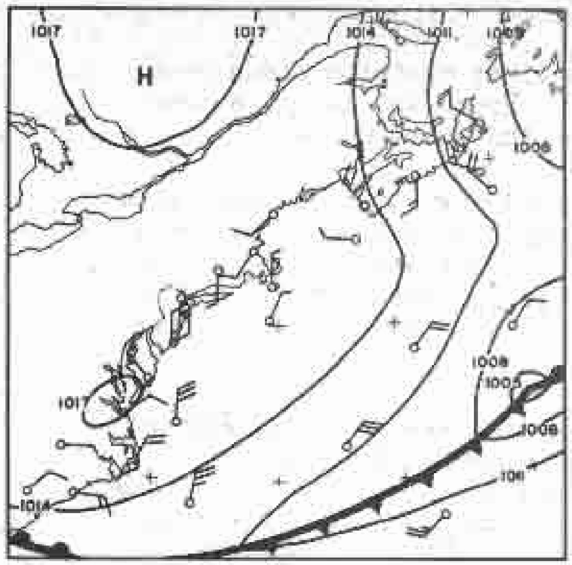
The map for May 4, 1930 EST shows continued advance eastward of the storm. The reported winds in the neighborhood of Long Branch are rather light and vary considerably in direction. Since the nineteen-knot winds mentioned above have died out, the waves generated by the winds from May 4, 1200 to 1700 were permitted to die down and the true build-up of the waves at Long Branch were considered to have started some time after May 4, 1700.

The map for May 5, 0130 EST shows that the approaching storm is an occlusion with a small wave in the warm front sector. The three reported coastal winds in the area of interest are southeast Beaufort three. The hourly observations of coastal winds showed that the winds are frequently stronger than Beaufort three especially to the south of Long Branch. The isobaric pattern indicates that the winds over the fetch were southeast over the generating area.

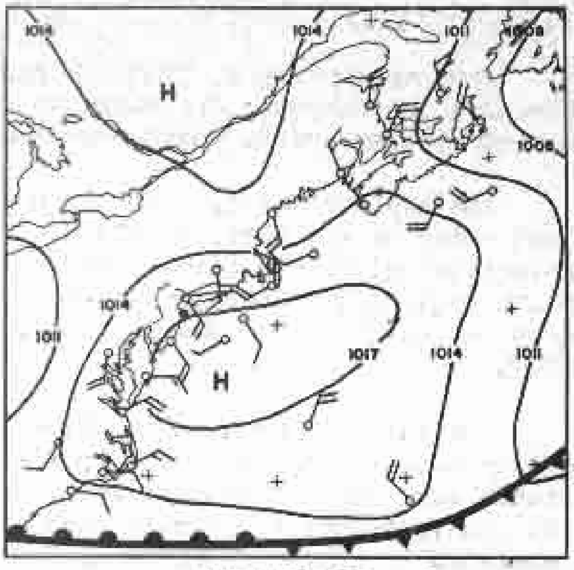
The map for May 5, 0730 EST shows the storm to be centered near Cape May, New Jersey. Reported winds over the area of interest are east Beaufort 7, 5, and 4; east south east Beaufort 5, and south east Beaufort 4. La Guardia reports dominately east south east winds from 0400 to 0800. The map suggests that the winds over the generating area should be east south east. (Note the large non-geostrophic wind components.)

The maps for May 5, 1330 and 1930 EST, shows the center of the storm moving off the coast. Northeast winds are reported at the coast, but strong east Beaufort 6 winds are reported offshore at 1930.

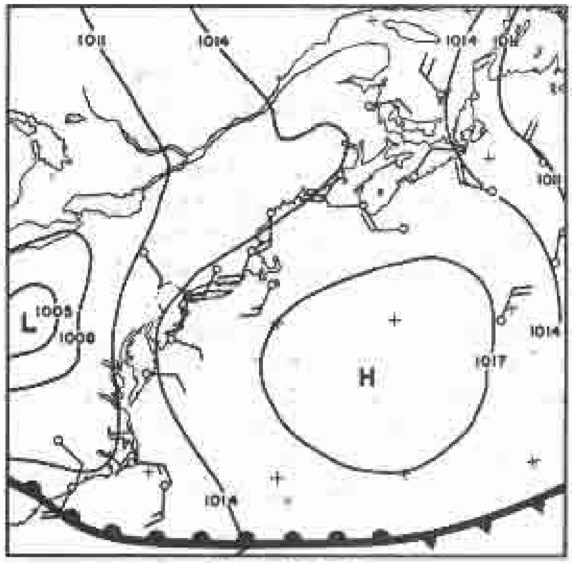
The reported significant wave heights increase until May 5, 2000 EST. Then the wave height drops three feet in four hours. The ascending portion of the height curve will be examined first. The winds over the generating area change gradually from south east Beaufort 3 to east Beaufort 6. The problem is to adapt this gradual change to the constant wind, constant direction methods which are necessary in the forecasting theory. By study of all the east coast hourly observations, mentioned in section 2, by study of the weather maps described above, and by adjusting the first values chosen in order to get a better height forecast fit, the following possible average wind field was chosen:



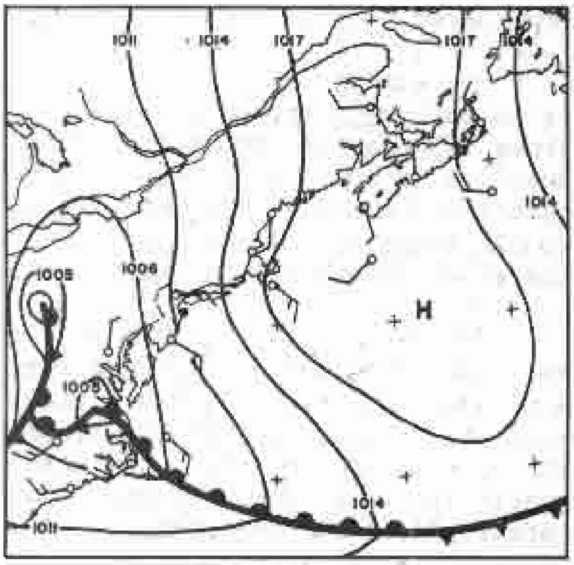
MAY 4 0730 EST



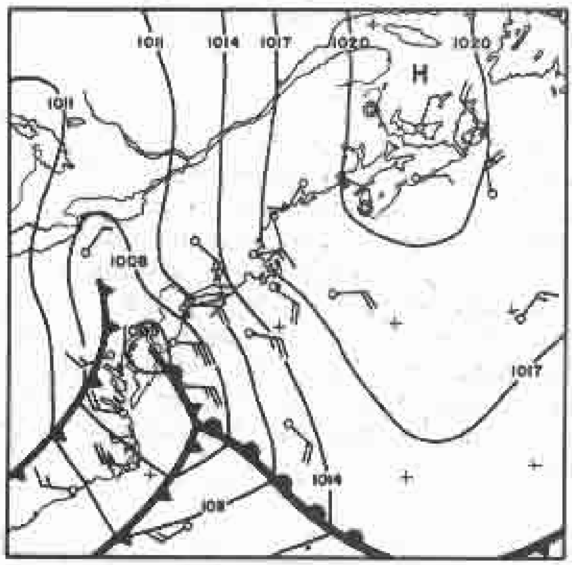
MAY 4 1330 EST



MAY 4 1930 EST



MAY 5 0130 EST

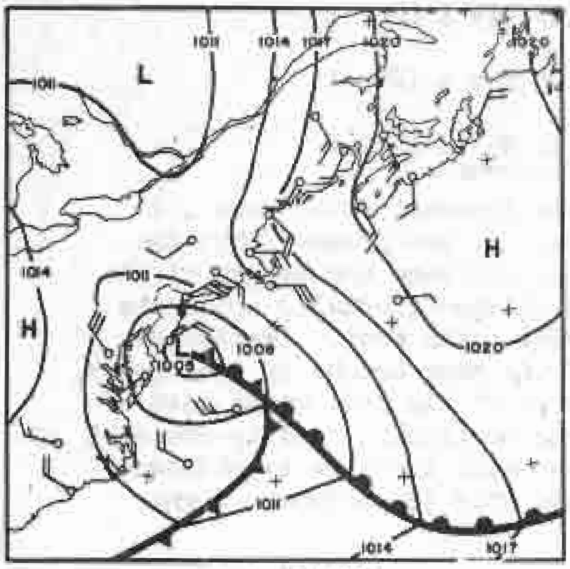


MAY 5 0730 EST

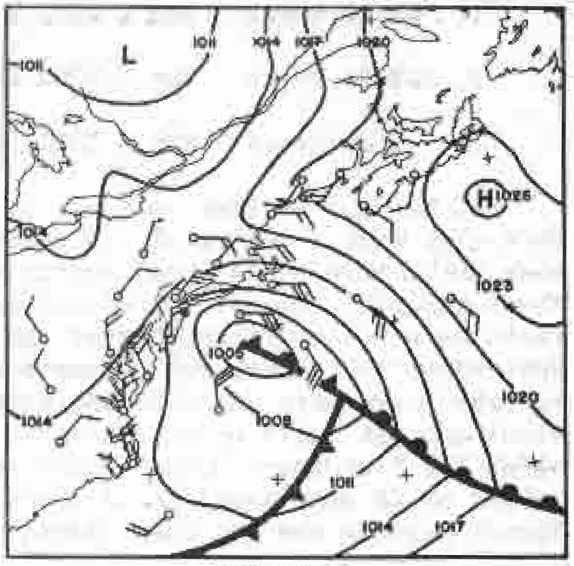
WEATHER MAPS OF AN EAST

HOURLY WINDS

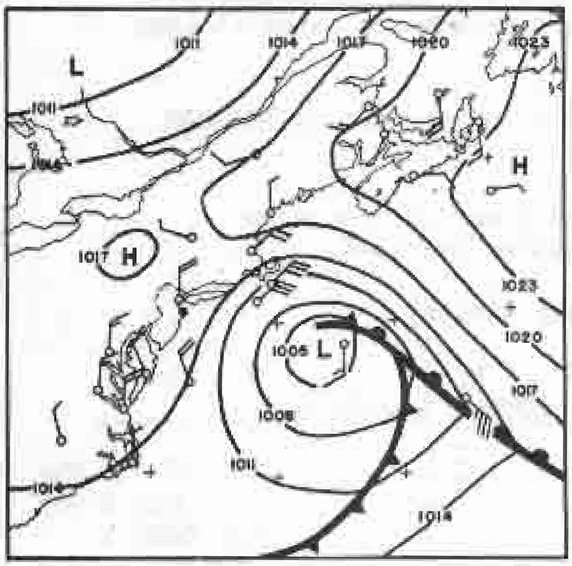
MAY 4	08	SW	10
	09	SSW	3
	10	SSE	5
	11	SSE	17
	12	SSE	15
	13	SSE	18
	14	SSE	20
	15	SSE	15
	16	SSE	18
	17	S	16
	18	SSE	14
	19	S	10
	20	S	12
	21	S	12
	22	S	8
	23	S	8
MAY 5	00	ENE	6
	01	E	10



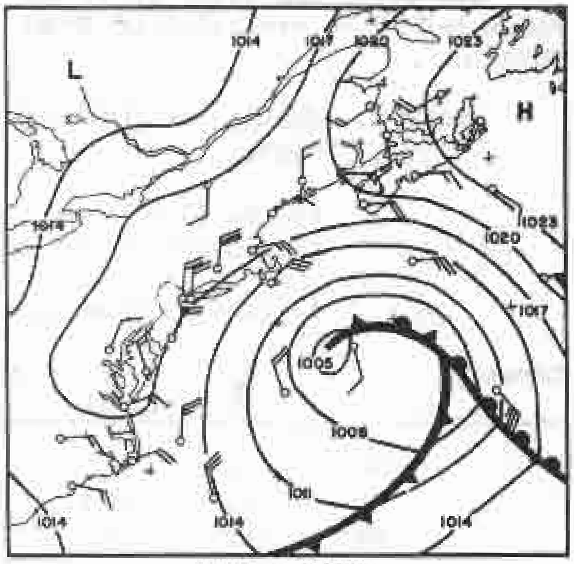
MAY 5 1330 EST



MAY 5 1930 EST



MAY 6 0130 EST



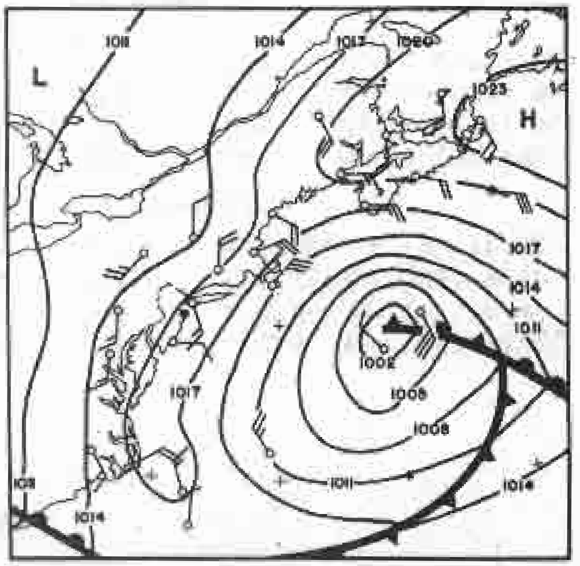
MAY 6 0730 EST

DURING PASSAGE
COAST STORM

(MPH) AT LAGUARDIA FIELD

02	ENE	12		20	N	21
03	ENE	10		21	NNE	25
04	ESE	11		22	NNE	19
05	ESE	14		23	N	18
06	SE	12	MAY 6	00	NE	22
07	ESE	13		01	N	17
08	E	15		02	N	23
09	ENE	16		03	N	14
10	NE	16		04	N	19
11	NE	20		05	N	14
12	NE	26		06	N	14
13	NE	39		07	N	17
14	NE	36		08	NNE	14
15	NE	33		09	NE	10
16	NE	30		10	NE	13
17	NNE	25		11	NE	13
18	NNE	28		12	ENE	12
19	NNE	21		13	ENE	12

FIGURE 9



MAY 6 1330 EST

1. SE 18 knots May 4 2000 E to May 5 0200 E

2. ESE 21 knots May 5 0200 E to May 5 1200 E

3. E 27 knots May 5 1200 E to May 5 1930 E

At the end of time interval 1, the forecast waves were 4.8 feet high with a period of 3.3 seconds. It was assumed that the east south east winds would continue to increase the height of the waves and that the wave direction had changed gradually until the waves were now traveling toward the west north west. Twenty-one knot winds would have raised waves of the same height in four hours, so four hours were added to the duration of the east south east winds and the build up of the waves was continued. Twenty-one knot winds for four hours do not raise waves with the same significant period as 18 knot winds for 6 hours and thus the forecast significant periods are not consistent.

The following table gives the procedure and the parameters which had to be evaluated in order to forecast the waves at Long Branch.

TABLE 7. EXAMPLE OF FORECASTS FOR TURNING AND INCREASING WINDS.

For 2h (+4h) = 6h, read true duration plus correction equals effective duration.

(Notation: Same as other tables)

Duration	H_F	T	REF	H_E	T	Time
	18 knots SE			2000 E to 0200 E		
2h	2.6	2.2	.95	2.5	2.2	2200 E May 4
4h	4.0	2.9	.94	3.8	2.9	0000 E May 5
6h	4.8	3.3	.92	4.4	3.3	0200 E
	21 knots ESE			0200 E to 1200 E		
2h (+4h) = 6 h	6.0	3.7	.93	5.6	3.7	0400 E
5h (+4h) = 9 h	7.2	4.3	.91	6.6	4.3	0700 E
7h (+4h) = 11h	7.6	4.7	.87	6.6	4.7	0900 E
10h(+4h) = 14h	8.0	5.1	.90	7.2	5.1	1200 E
	27 knots E			1200 E to 1930 E		
2h(+4.5h) = 6.5h	9.5	4.5	.93	8.8	4.7	1400 E
4h(+4.5h) = 8.5h	10.5	5.1	.94	9.7	5.1	1600 E
6h(+4.5h) =10.5h	11.2	5.4	.95	10.7	5.4	1800 E
7.5h(+4.5h) =12. h	12.0	5.7	.96	11.5	5.7	1930 E

The height forecasted by the above procedure follow the observed height curve and also the slopes of the two curves coincide. Note that the forecasted period decreases from 1200 E to 1400 E and that the method is inconsistent in the forecast of significant periods. Any attempt to find one constant wind speed and direction applicable over the entire forecast period would have led to large inconsistencies in the heights, and probably no better forecasts for the periods. The decrease in wave project significant period from 1200 EDT to 1600 EDT is probably accidental.

As the storm moved away from the New Jersey coast, the difficulty in applying the concept of a fetch with a wind of constant direction and constant speed to the actual cyclonic winds in the storm became evident. The winds at La Guardia and also along and offshore from the coast were northeast and north north east for nine hours during the time when the waves were being forecast by a due east twenty-seven knot wind. North east winds can be effective only over a twenty-five nautical mile fetch. Thirty-five knot north east winds could have generated waves eleven feet high before refraction on May 5, 1300 EST, but the peak height would then have occurred six hours before the observed peak height. The average value of the winds at La Guardia from 1000 to 1900 is twenty-four knots. With a twenty-five nautical mile fetch the waves before refraction would have been at most only seven and one half feet high. A study of figure 5 shows that the waves decreased rapidly in height from May 5, 2000 EST to May 5, 2400 EST. A study of Figure 4 for April 28 and 29 shows that waves for that previous storm did not decrease as rapidly after the peak height had been reached. The sharp drop in wave height is probably partially due to the very strong winds at a sharp angle to the waves of the main fetch oriented eastwest. The concept of the variability in the direction of waves coming from a fetch does not seem to be applicable because it does not explain this very sharp drop in wave height.

It is possible to find a partial explanation for the wave heights observed on May 5, 2400 EDT and May 6, 0400 EDT. If 27 knot winds from 52° east of north are chosen to represent the averaged effect of north and northeast winds at La Guardia and north east and east winds at Nantucket, a thirty mile fetch results. Waves 9.0 feet high with a 4.4 second period with heights after refraction of 8.1 feet are then obtained.

The waves which occurred after May 6, 0400 were forecast as waves arriving from distant fetches. The curve for the lower forecasted heights which runs from May 6 through May 8 was all the result of waves generated by the storm shown in Figure 9 as that storm moved out over the Atlantic Ocean.

The map for May 6, 1330 EST shows another low on the western edge of the map. A warm front is approaching Cape Hatteras. A secondary storm is approaching the east coast. The second increase in wave height on May 7 and May 8 was caused by this secondary storm. The secondary storm will be discussed when examples of superimposed wave forecasts are described later.

The east coast storm of May 13, 14, 15, and 16, can now be compared with the east coast storm of May 4, 5, 6, 7 and 8. The second storm (Figure 6) shows a build-up of the reported wave heights without a sudden rise as at May 5, 1200. The waves in the second storm were generated by winds from the east north east instead of east winds and the level top of the curve occurred because the waves had reached an upper limit on height and period fixed by the limitation of the length of the fetch. In the second storm the winds shifted to north east and north east (as in the first), and the wave height dropped five feet in eight hours. The forecasts after May 14, 1600 are again based upon the decay of waves from a distant fetch, but no secondary storm follows close after the primary storm and the waves dwindle down to heights of one and one half feet. Note also that the wave project significant period partially follows the sharp drop in forecasted significant period, which follow the maximum observed height, but that the low values of the significant period were not observed for the length of time that they were forecast. In the first storm the forecasted drop in period was apparently not observed.

Figure 10 and 11 consist of three minute sections of the wave records which were obtained during the passage of the east coast storm of May 4, through May 8. Many of the points made in Section 3 are evident in these wave records. In particular, counterparts of record B in Figure 3 can readily be found.

The wave record in Figure 10 for May 4 at 0800 shows smooth waves from the small disturbance of May 3. At 1200, the build-up of the first minor waves can be seen. They were caused by the south south east winds mentioned in the discussion of the May 4, 1330 surface map. There is some evidence that these waves die out again by May 4, 2000 EDT. Note the extreme irregularity of these records.

The build-up of the waves from the major storm started on May 5 000. The increase in the significant height from record to record is evident although the variation in the significant period is not obvious.

The peak recorded storm wave height was reached on May 5, 2000 as shown in Figure 11. Some of the individual waves in this record are over seventeen feet high. Thereafter the wave heights decrease during the passage of the major storm.

The record for May 7, 1600 is of great interest. All indications are that there should be two wave trains present in the record. A nearby storm has generated 6.7 foot forecasted waves with a 4.0 second forecasted period, and the distant storm which started on May 4

WAVE RECORDS AT LONG BRANCH
DURING PASSAGE OF AN EAST COAST STORM

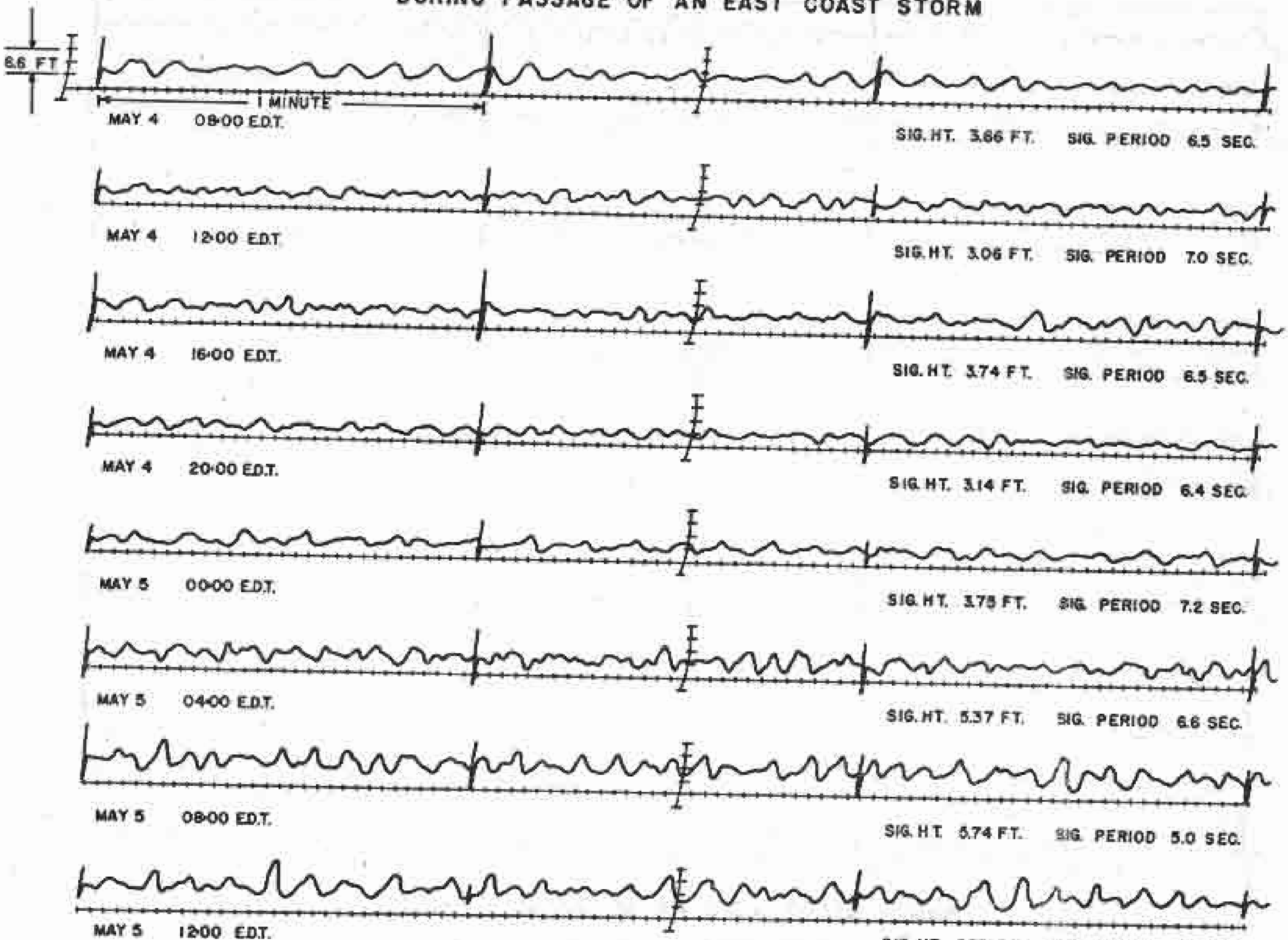


FIG. 10

WAVE RECORDS AT LONG BRANCH

DURING PASSAGE OF AN EAST COAST STORM

FIG. II

is still causing 2.5 foot forecasted waves with an 8.? second forecasted period. (See Figure 5). To date, it has not been possible to discover any method of significant wave analysis which can discover any difference between this record and, say, the record for May 6, 0800.

4. Example of a Hurricane and Associated Wave Records. A tropical storm which first developed near Riding Rock in the Caribean moved north north eastward to a point about two hundred miles west south west of Bermuda. Then it recurved and moved south eastward about three hundred miles to a point about four hundred miles south south westward of Bermuda. The hurricane stagnated at this point for a day and a half, and then moved northward, erratically. The storm weakened rapidly as it moved northward, and it dissipated completely by the time it was due east of Long Branch. Figure 12 shows the path of the storm center, and some other pertinent data about the storm.

The arrival of the first waves from the distant hurricane is somewhat obscured by the presence of local wind waves offshore from Long Branch. Light south east winds were blowing to a considerable distance offshore from Long Branch on May 24th and on May 25th until about 1200 EDT. Waves were forecast by the decay in fetch method from the above time until May 26, 1000 EDT as shown in Figure 7.

It might seem that for a distant hurricane, it should be possible to decide upon an accurate deep water direction for the waves approaching Long Branch. However, this is not the case. The radius of the hurricane, for example, on May 24, 1330 was 250 nautical miles. The winds in the storm in the sector formed by a line running northeast through the center and southeast through the center were southeast as it moved from its point of origin to the position it occupied on May 24, 1330.

It was possible to find a generating area over which the winds increased from Beaufort five to Beaufort seven as the storm moved from its origin to its May 24, 1330 position. A line connecting Bermuda and the 1930 May 25 position could represent the windward edge of the fetch except that the right side of the fetch was about one hundred fifty miles short of Bermuda. Since the waves can come out of the fetch at an angle, it is possible to choose a deep water wave direction with any azimuth from 145° to 160° (Figure 1). An azimuth of 145° was chosen to avoid the problem of multiple waves at Long Branch. The forecast curves for the wave height and period from May 25, 1200 to May 26, 1400 in Figure 7 were obtained from forecasts from this fetch. The last few forecasts based upon this fetch were somewhat in doubt.

Similarly the deep water wave direction is in doubt for all other hurricane forecasts. In fact, the difficulty in choosing one value to represent the wave direction is similar to the difficulty

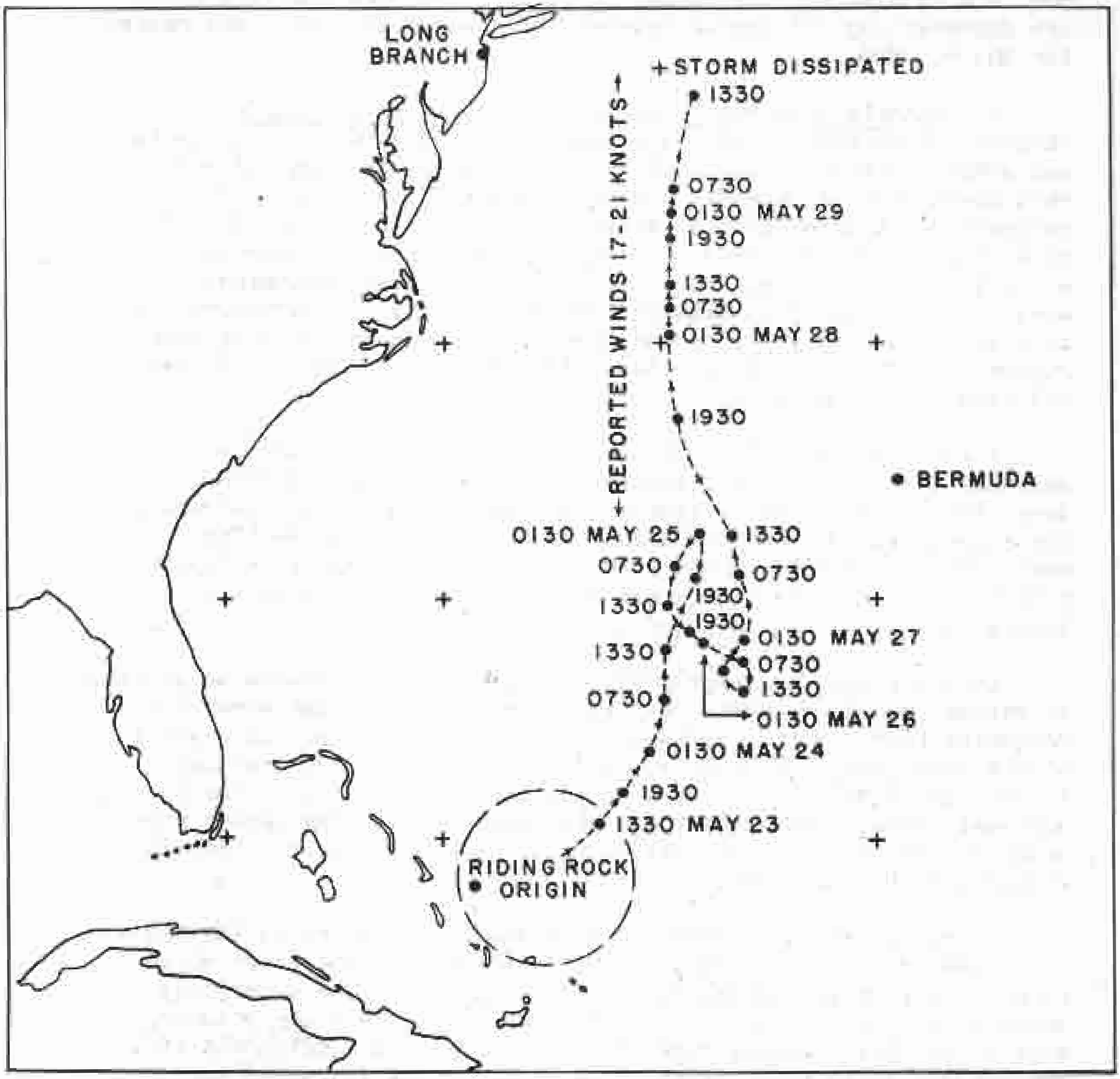


FIG. 12 PATH OF AN EAST COAST HURRICANE WHICH OCCURED FROM MAY 24, 1948 TO MAY 29, 1948

in choosing one value for the wave period. These points will be discussed again when the problem of verifying the wave refraction diagram is discussed.

A generating area which was the same for seventy-two hours could be found as the storm moved from its May 24, 0130 to its May 27, 0130 position. The decay distance was essentially five hundred and fifty nautical miles for all of the above time interval. The deep water direction was chosen at an azimuth of 145°. Beaufort 5 and Beaufort 6 winds were reported equally often over the generating area and light winds were reported over the area of decay. A value of twenty-two knots was chosen for the wind velocity over the generating area.

It may seem strange that a generating area in a hurricane would have twenty-two knot winds over it. At this stage of its development the storm undoubtedly had winds of hurricane force (75 mph) near its center. However the hurricane force winds would be blowing around a tight little circle near the center, and it is difficult to see how the concept of a fetch can be applied to the hurricane center. The generating area chosen did fit the usual concepts of a fetch in that winds fairly uniform in direction and speed were found over the entire area.

The forecast parameters which were evaluated in order to forecast waves at Long Branch from the distant hurricane are given in Table 8.

The forecast versus the observed values as graphed in Figure 7 for the above fetch, wind, and duration show some points of interest. The forecasted wave height decreases after May 26, 2300. Yet the waves in the generating area were increasing in height, and their forecasted height before refraction was also increasing with time. The decrease in height is entirely due to refraction. Thus the decrease in wave height might seem to be a good verification of the refraction diagram. This is not the case, however. The trend of the observed periods is downward, if anything, and the forecast and observed periods do not agree.

Donn (6) gives an example which shows the decrease of swell period with time from a tropical cyclone of September 12-15, 1946. This example is therefore not an exception to the general rule. However, in both cases it is very difficult to take into consideration the effect of refraction since the swell in deep water may have a spectrum of periods.

Two other fetches were located as the hurricane moved northward and before the hurricane dissipated. Forecasts from them were not of particular interest, and they will not be discussed in detail. As the hurricane moved northward much stronger opposing winds were found over what had been the fetch used for the forecasts

TABLE 8. WAVE FORECASTS AT LONG BRANCH FOR WAVES FROM A DISTANT HURRICANE

Start of winds over fetch May 22, 0130 E; 22 knots; 550 nautical mile decay distance; deep water azimuth 145°. (Notation: Same as previous tables).

Duration	H_F / T_F	H_D/H_F / T_D	Ref.	Travel Time	Forecast H_r / T / Time
+ 6h	6.3 3.8	.11 8.6	.5	41 hrs	.35 8.6 May 26, 0300
+12h	8.0 5.0	.19 9.1	.4	39 hrs	.60 9.1 May 26, 0430
+18h	9.0 5.6	.25 9.6	.5	38 hrs	1.1 9.6 May 26, 0930
+24h	10.0 6.4	.3 10.1	.7	36 hrs	2.1 10.1 May 26, 1330
+30h	10.5 7.2	.36 10.4	1.1	34 hrs	4.2 10.4 May 26, 1730 E
+36h	10.5 7.5	.39 10.8	1.1	33 hrs	4.5 10.8 May 26, 2230 E
+42h	10.5 8.0	.41 11.1	.8	32 hrs	3.5 11.1 May 27, 0330 E
+48h	10.5 8.2	.42 11.2	.8	31 hrs	3.5 11.2 May 27, 0830 E
+54h	10.5 8.6	.45 11.4	.7	31 hrs	3.3 11.2 May 27, 1430 E
+60h	10.5 9.0	.48 11.5	.7	30 hrs	3.4 11.5 May 27, 1930 E
+66h	10.5 7.4	.50 12.2	.4	30 hrs	2.1 12.2 May 28, 0130 E
+72h	10.5 9.8	.51 12.6	.3	29 hrs	1.6 12.6 May 28, 0630 E

WAVE RECORDS AT LONG BRANCH

GENERATED BY A DISTANT HURRICANE

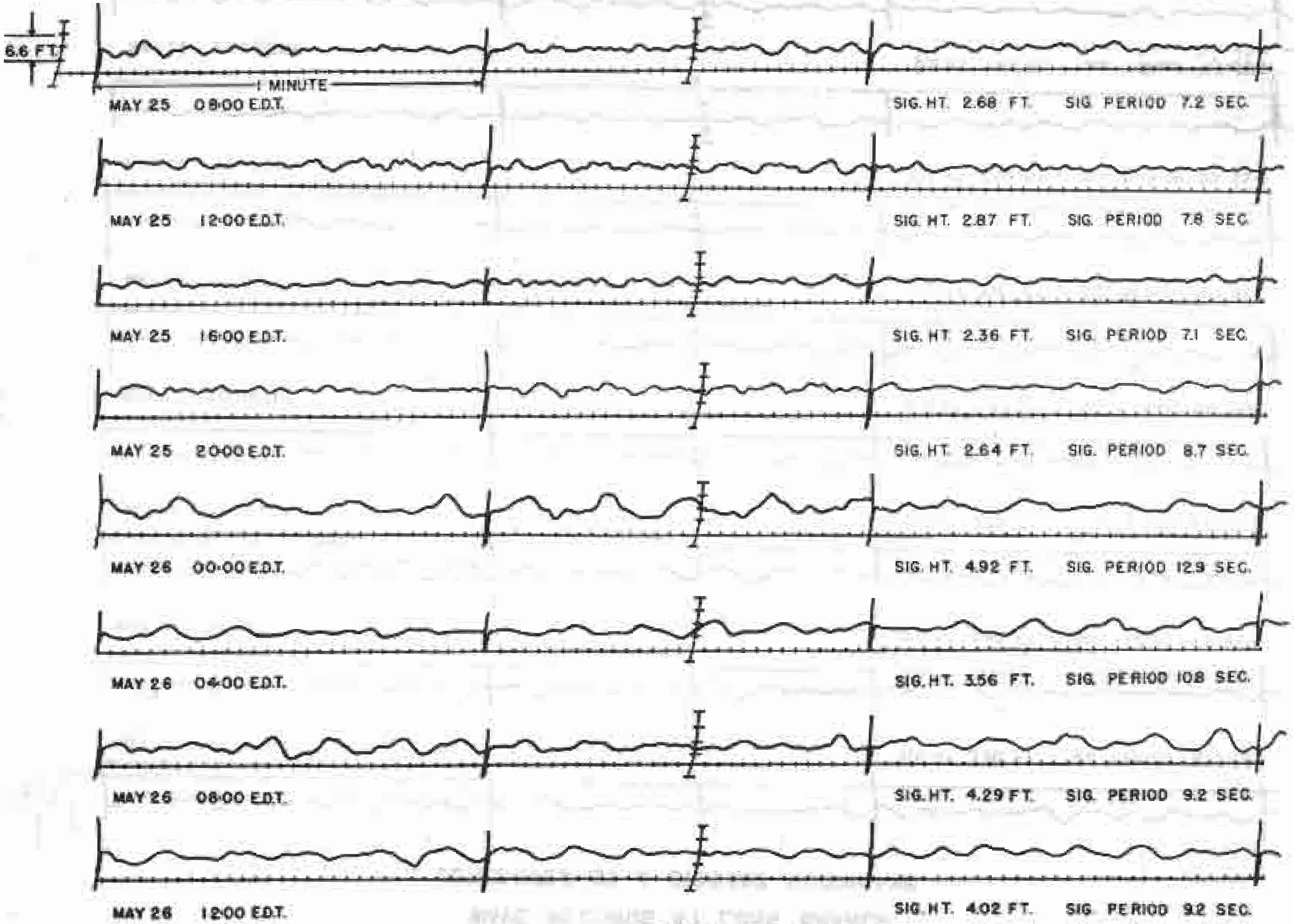


FIG. 13

WAVE RECORDS AT LONG BRANCH GENERATED BY A DISTANT HURRICANE

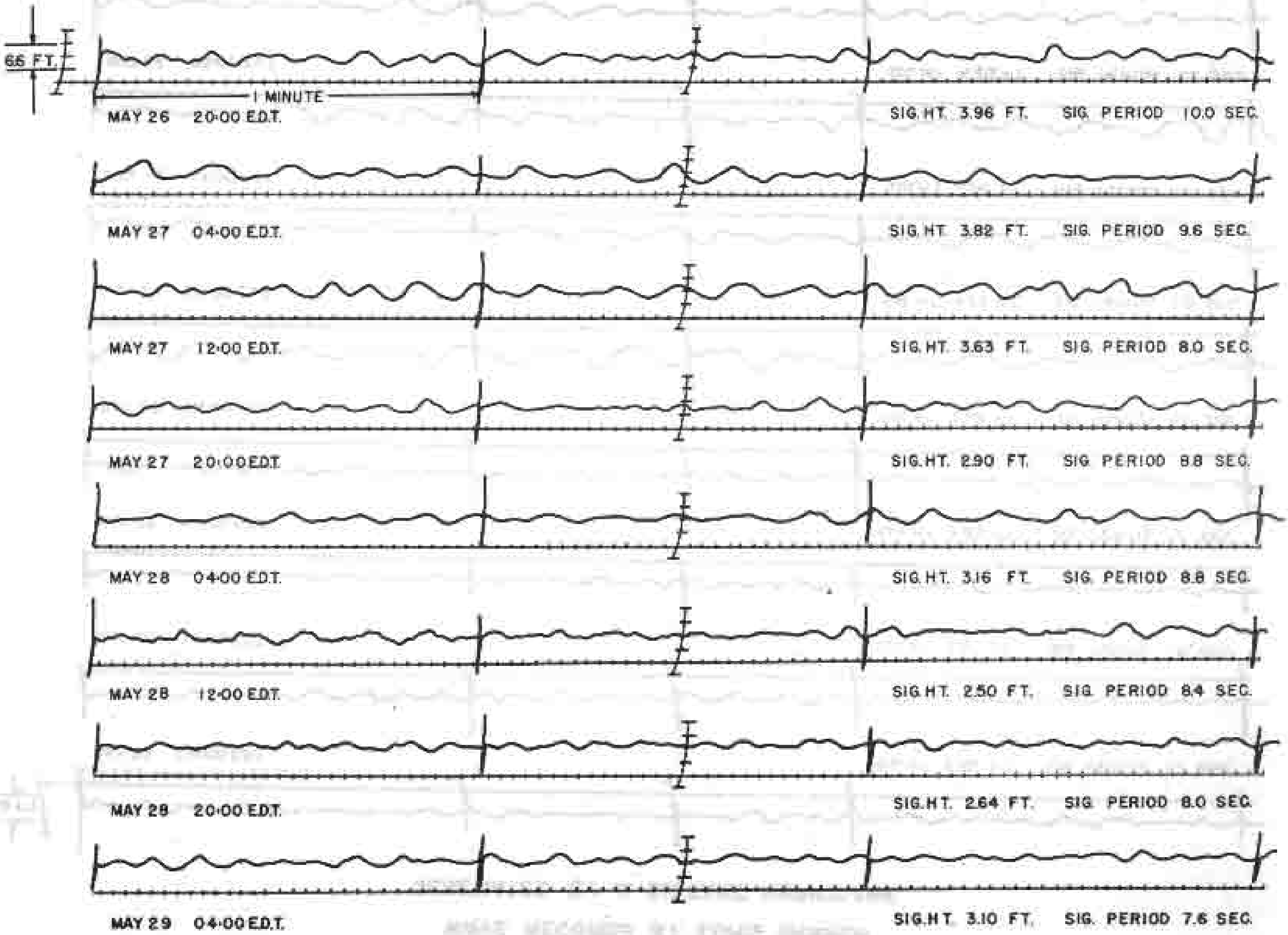


FIG. 14

in Table 8; and therefore, the decay in fetch method was not used.

Some of the wave records which were obtained from the distant hurricane are shown in Figures 13 and 14. Three minute segments of the wave record are shown. The records in Figure 13 cover the period from May 25, 0800 to May 26, 1200. The records from May 25, 0800 and May 25, 1200 were theoretically recorded before the arrival of the distant swell from the hurricane. They show very irregular local wind waves. At May 25, 1600, the distant swell has theoretically arrived, but it is difficult to see any difference between this record and the two records above. Similar remarks hold for the wave record of May 25, 2000. The wave record for May 25, 2400 shows that the swell from the distant hurricane has definitely arrived. The swell itself is quite irregular, and some local wind waves are probably superimposed upon it. The records which follow are quite smooth, and the local waves are no longer in evidence.

Figure 14 shows the wave records at eight hour intervals from May 26, 2000 to May 29, 0400. It is possible to see the tendency toward an apparent decrease in period from record to record. The decrease in height is also evident.

5. <u>Examples of Superimposed Wave Forecasts and Associated Wave Records</u>. A survey of Figures 4, 5, 6, and 7 shows that there were a number of cases in which two or more different significant waves were forecasted to arrive at Long Branch at the same time. In some cases it was possible to see the low period local wind waves superimposed upon the higher period swell from a distance. In other cases the various wave trains could not be separated one from the other.

Figure 15 shows some of these records. The records for April 25, 0800, 1200 and 1600 are one group to be considered. Figure 4 shows that high period swell from a distant fetch was arriving at Long Branch at 0800, 1200 and 1600. Figure 4 also shows that local wind waves began to build up after 0800. The first wave record in Figure 5 shows the minor short period local wind waves superimposed on the distant swell. The third wave record shows that the local waves have built up in height and that the supposedly still present distant swell cannot be detected.

The records for May 7, 0800 and 1200 are another group to be considered. These records were made during the passage of the secondary storm following the primary storm which occurred on May 4, 5, 6, and 7 as shown in Figure 5. The forecasts indicate that higher period swell from the distant storm is still present, but there seems to be no way to separate the two forecasted wave trains. See also the records in Figure 11.

The last two records in Figure 15 for May 11, 1600 and 2000 were made when three different wave trains were forecasted to

WAVE RECORDS
FOR EXAMPLES IN WHICH MULTIPLE
WAVES WERE FORECASTED

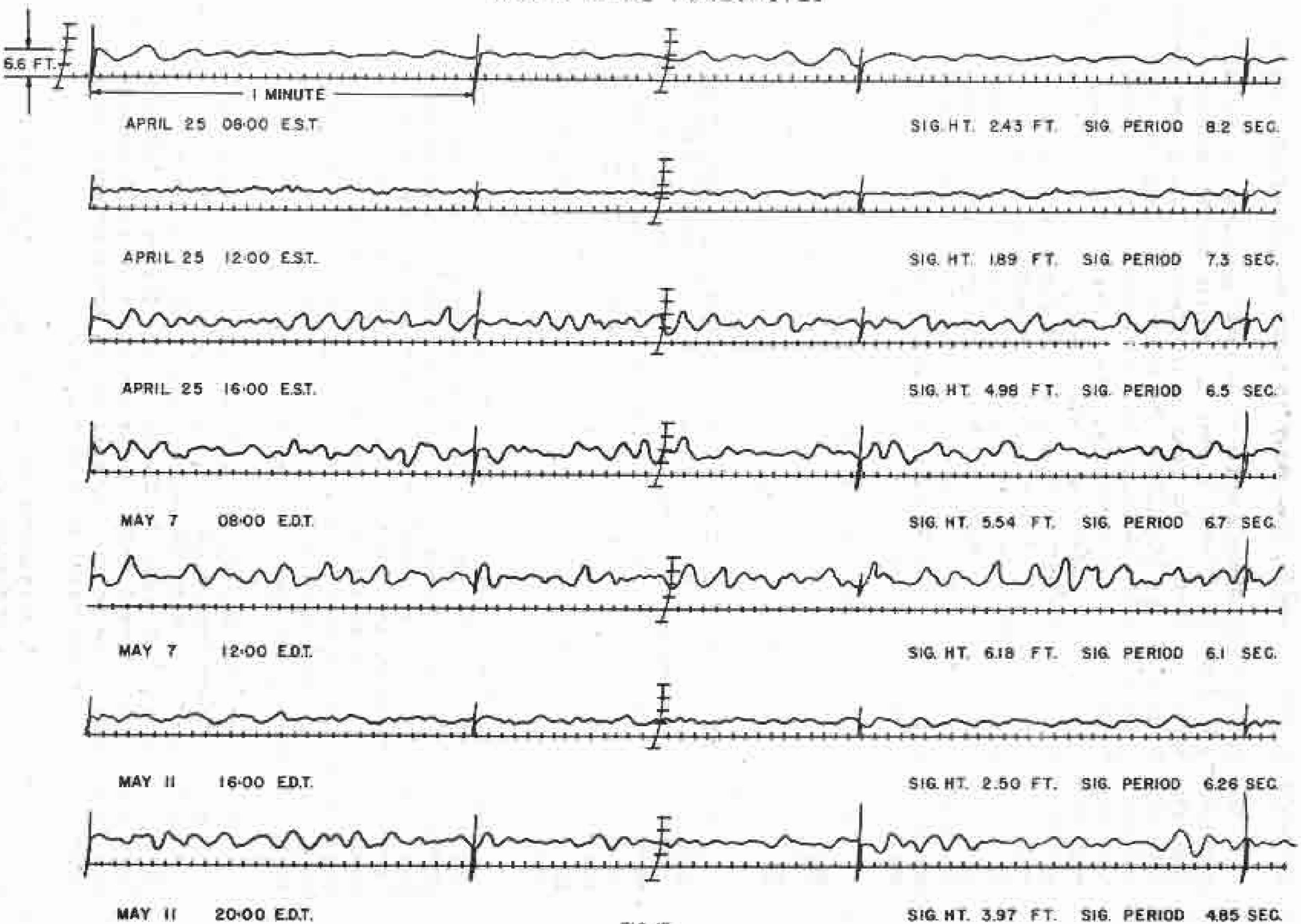


FIG. 15

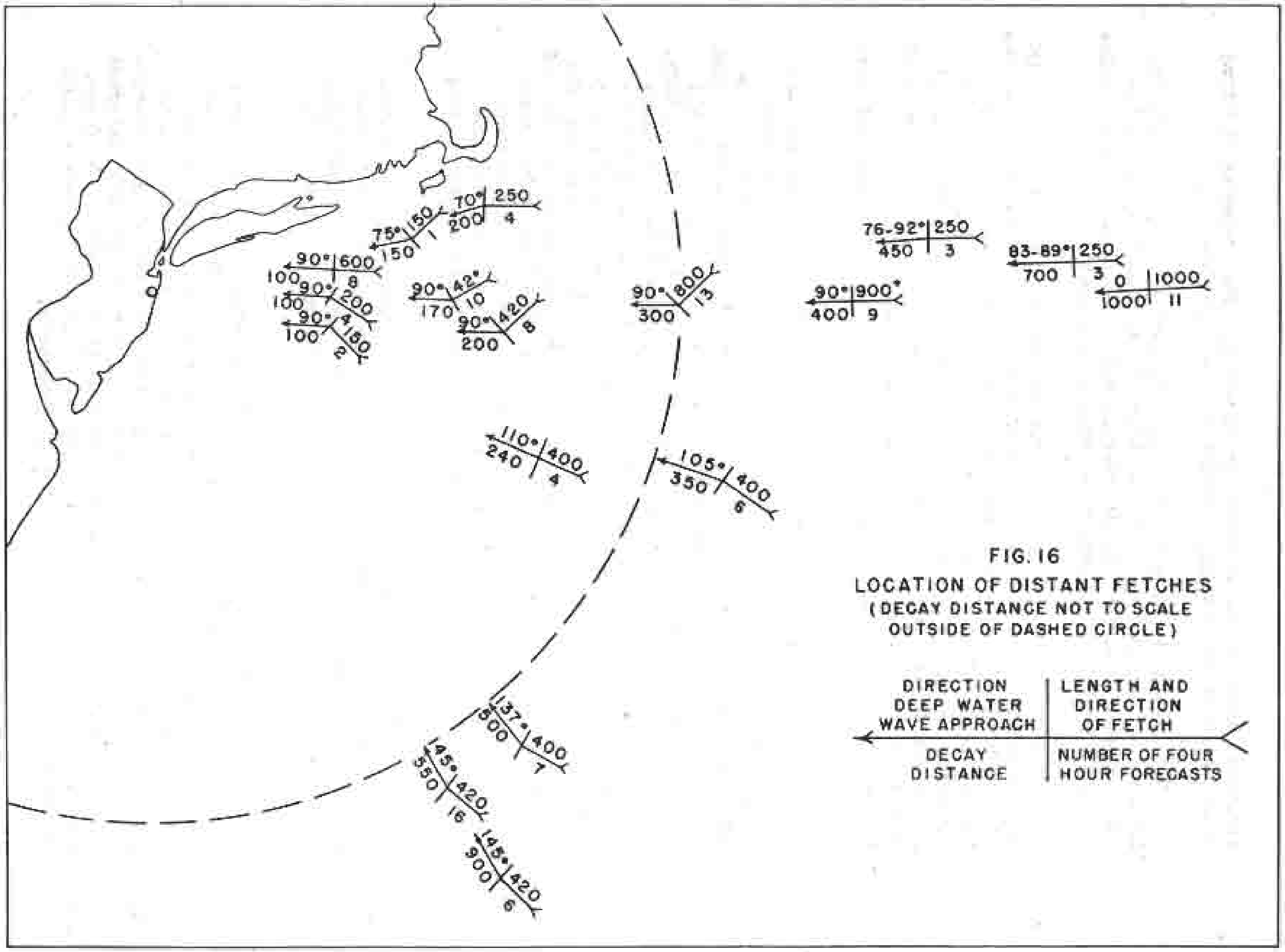


FIG. 16
LOCATION OF DISTANT FETCHES
(DECAY DISTANCE NOT TO SCALE OUTSIDE OF DASHED CIRCLE)

arrive at Long Branch as shown in Figure 5. The presence of three wave trains is not visibly evident in the records.

Note again the wave records at the start of the hurricane in Figure 13. In summary, in a few cases it is possible to see the superimposed local and distant waves, but in most cases, the various forecasted wave trains cannot be separated visually.

In addition to the general forecast techniques which have just been described, it is possible to give additional information on the overall nature of the forecasts by showing the location of the distant fetches and the frequency of occurrence of fetches which terminate against the coast. The deep water wave direction as picked for the forecasts, although somewhat inaccurate, is important in problems connected with beach erosion and the figures to be discussed will show the frequency of occurrence of the various deep water wave directions.

A distant fetch is defined as a fetch or generating area separated from the observation point by an area of relative calm through which the waves must travel. Cases in which decay in the fetch was used but in which the fetch originally terminated against the coast are not included. Figure 16 shows the location of all of the distant fetches which were found during the period of study. The arrow indicates the direction that the waves were considered to leave the fetch. The number above the arrow is the direction of deep water approach to the coast; 90° is due east, 135°, southeast, etc. The number below the arrow is the decay distance. The bar is located at the near end of the fetch. The angle between the bar and the arrow represents the angle that the waves were taken out of the fetch according to Arthur's (1) theory. The number above the tail of the arrow is the length of the fetch and the number below is the number of four hour wave forecasts which were obtained from the given fetch.

Some of the broken arrow symbols are displaced slightly from their true position because they would be too crowded if located correctly. Their correct position can be inferred from the data. Outside of the dashed circle the decay distance is not to scale for some of the symbols.

There are seventeen distant fetches located on the diagram, and they represent 115 four hour forecasts. There were 226 four hour observations during the period studied. Thus, neglecting overlapping forecasts, of which there were 44, the above distant fetches account for about 50% of the waves observed at Long Branch. Of these distant fetches, six required the use of Arthur's diagrams involving variability in the direction of wave travel. The forecasts based on Arthur's work and involving distant fetches account for about 18% of the total number of forecasts.

The distant fetches do not appear to be equally distributed with respect to the deep water direction of wave approach to Long Branch. There are no close-by distant fetches to the south and southeast, because for the period studied, such fetches all terminated against the coast. The direction of deep water approach should be considered accurate only to within plus or minus 15° since the width of the generating area permits considerable arbitrariness in the choice of wave direction.

The local fetches all terminated against the coast at the start of the forecast unit. Cases in which the decay in fetch method was employed are included. To within an accuracy of sixteen points of the compass, the deep water wave directions and the total number of four hour forecasts for each direction are shown in Figure 17. For example, there were 15 four hour forecasts for waves from due south. Of the total of 136 four hour forecasts, 88 four hour forecasts were from a direction with a southerly component, 14 four hour forecasts were from due east and 34 four hour forecasts were from a direction with a northerly component. Thus according to Putnam, Munk and Traylor (15), 60% of the local waves would produce a northward littoral current, 10% would be indeterminate, and 30% would produce a southward littoral current.* In addition, 20% of the forecasts were based upon Arthur's results on the variability in wave direction.

Section 7. Analysis of Forecasts

As pointed out in the previous sections, the trial forecasts were carried out in order to obtain the best possible agreement in the height forecasts. In many cases, it was not possible to get agreement in the period forecasts. In other cases partial success was obtained during part of a given forecast sequence; but, after initial good agreement was obtained, the forecasts dictated by the original choice of forecast parameters became progressively poorer in time. When the times of the forecast did not agree with the observation times, the forecasts were interpolated linearly.

In the discussion which follows, the forecast data will be divided into three main categories. Multiple valued forecasts, that is, those forecasts in which two or more significant wave trains were forecasted to arrive at Long Branch, will be discussed first. Then all single valued forecasts, both those based on the Sverdrup-Munk extended theory and those based upon the decay in fetch method, will be analyzed. Finally the purely Sverdrup-Munk forecasts will be separated from the decay in fetch forecasts

*The above estimate is somewhat crude. The direction of the waves as they cross the three fathom line depends also on the period as shown in the refraction diagram obtained by Pierson (14).

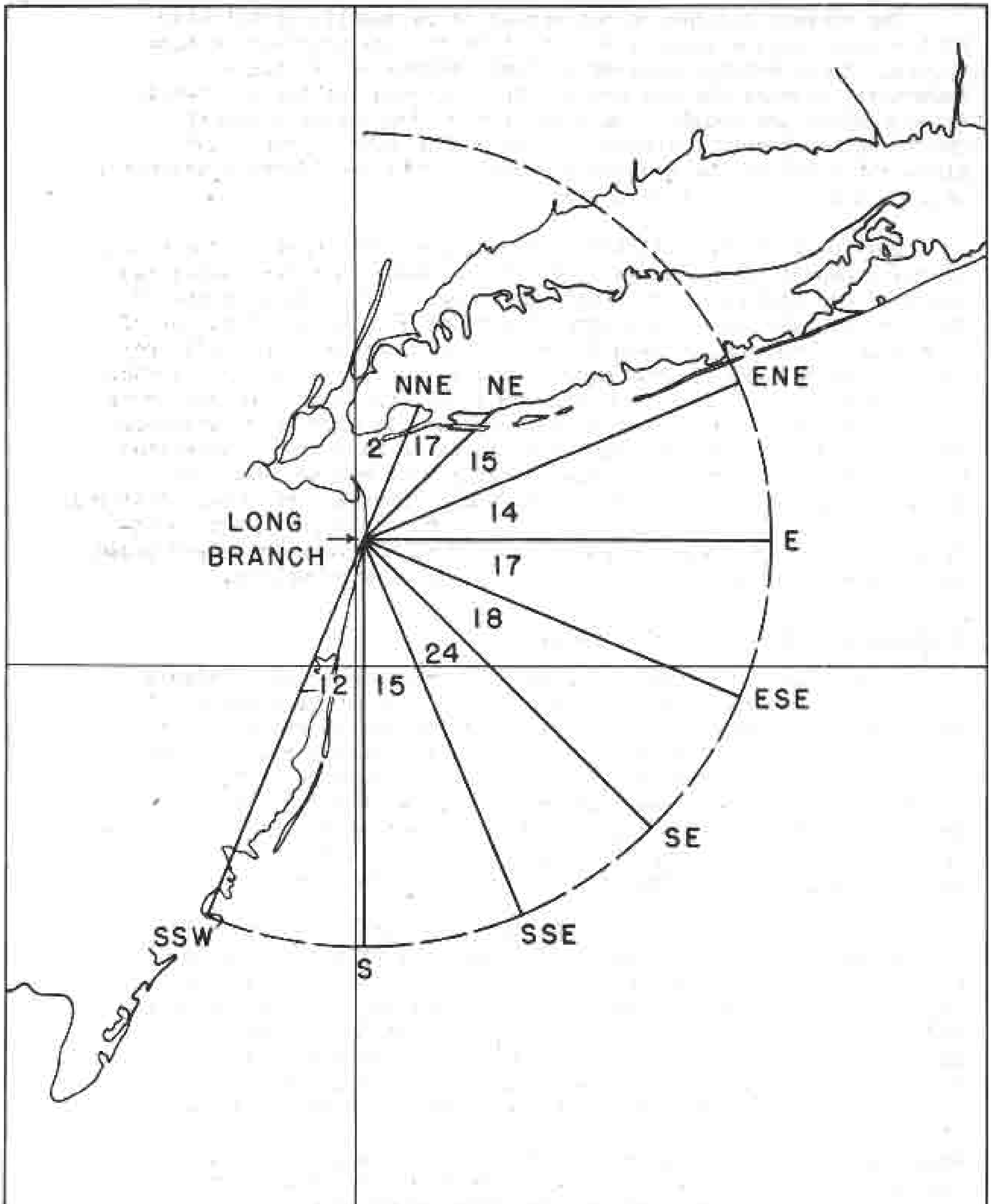


FIG. 17 NUMBER OF FOUR HOUR FORECASTS FOR VARYING DEEP WATER WAVE DIRECTION. FETCH TERMINATES ON COAST.

and the results analyzed.

Multiple valued forecasts. There were forty-four cases in which two or more different significant wave trains were forecasted to arrive at Long Branch at the same time. As shown in Section 6, sometimes it was possible to see that the two wave records superimposed, but usually it was not possible. When several significant heights are forecasted at the same time there are two possible simple ways in which they can be combined to obtain the one observed significant height. One way is to forecast the sums of the forecasted significant heights, or H forecast = $H = H_1 + H_2 + \ldots\ldots$ The other way is to forecast the square root of the sum of the squares of the significant heights, or

$$H \text{ forecast} = H_{rms} = (H_1{}^2 + H_2{}^2 + \ldots)^{\frac{1}{2}}$$

The first way would be more plausible if the waves added one on top of the other, and if the periods were nearly the same. The second way would be more plausible if the significant heights were more nearly related to the energy of the wave train.

Figure 18 shows histograms of the number of forecasts for each height interval. The sum of the heights is always greater than the RMS height, and thus much higher values were forecast by the sum of the heights method.

Figure 19 shows the histograms of the errors with regard to sign of the two methods. Forecasts which were too high are plus values, and forecasts which were too low are minus values. The histogram of the errors in the RMS heights is centered nearly about the zero error line, whereas the histogram of the errors in the Σ heights is centered about an error of about 1.3 feet. The mean absolute RMS error was .68 feet, and the mean absolute Σ height error was 1.38 feet. Statistically then, the RMS forecasts are better than the Σ height forecasts. The existence of a method which is better than either of the two is not precluded.

There does not seem to be any logical method for combining two forecasted significant periods in order to obtain one observed significant period. If the strict definition of periodic (in the sense of a wave train with one period and one height) is accepted, any such attempt would be absurd.

All single wave forecasts. There were one hundred and eighty three forecasts in which only one value for the significant wave height and period was forecast. The distribution of the observed and forecasted heights for this group, of the errors in the forecasted heights, of the observed and forecasted periods and of the errors in the forecasted periods will be discussed in order.

Figure 20 shows histograms of the height distributions of interest. The upper values of the histogram at the top give the

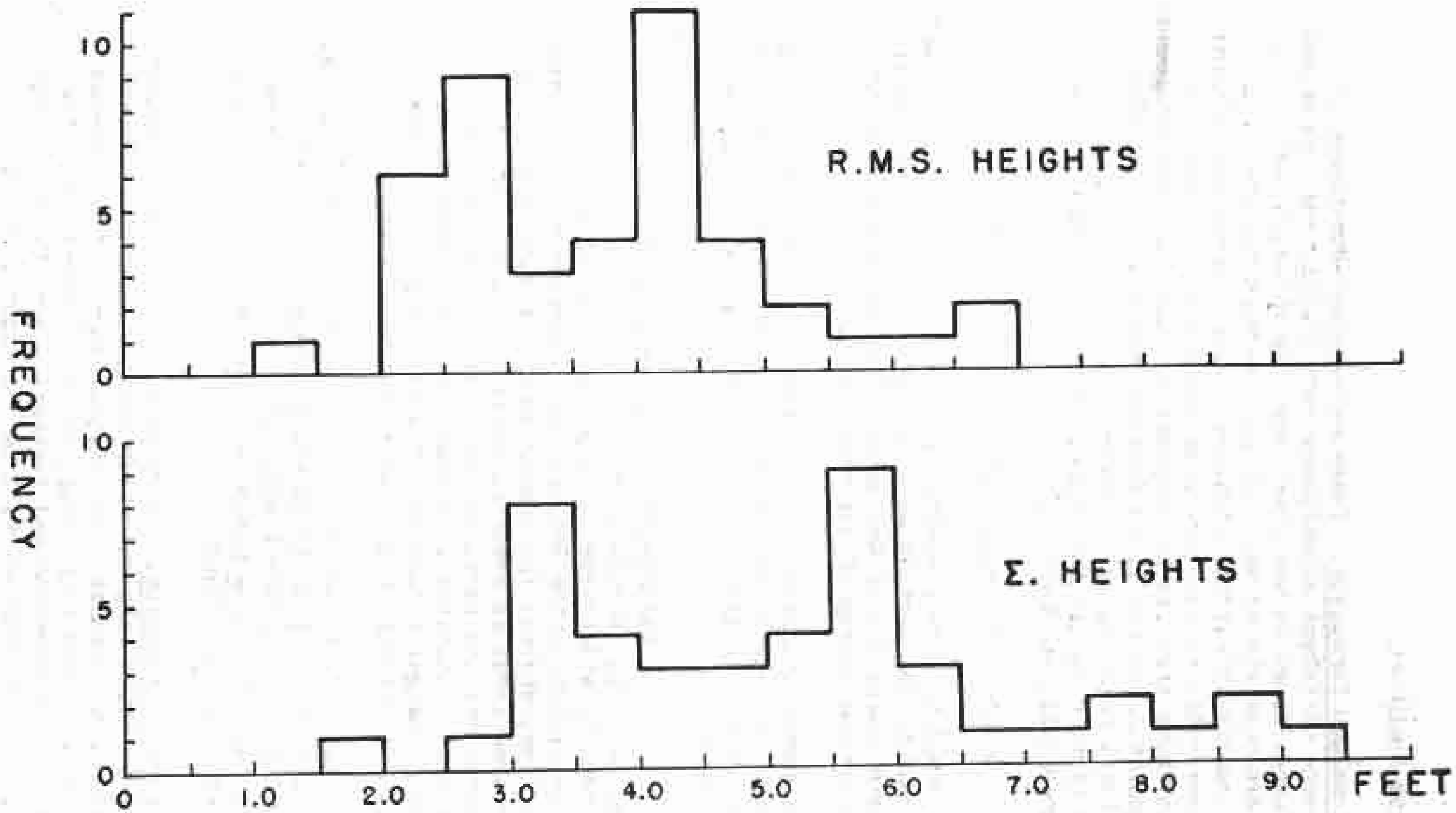


FIG. 18 HISTOGRAMS OF HEIGHT FORECASTS FOR THE TWO DIFFERENT METHODS EMPLOYED WHEN MULTIPLE FORECASTS OCCURRED

Σ. HEIGHTS = $H_1 + H_2$

R.M.S. HEIGHTS = $(H_1 + H_2)^{\frac{1}{2}}$

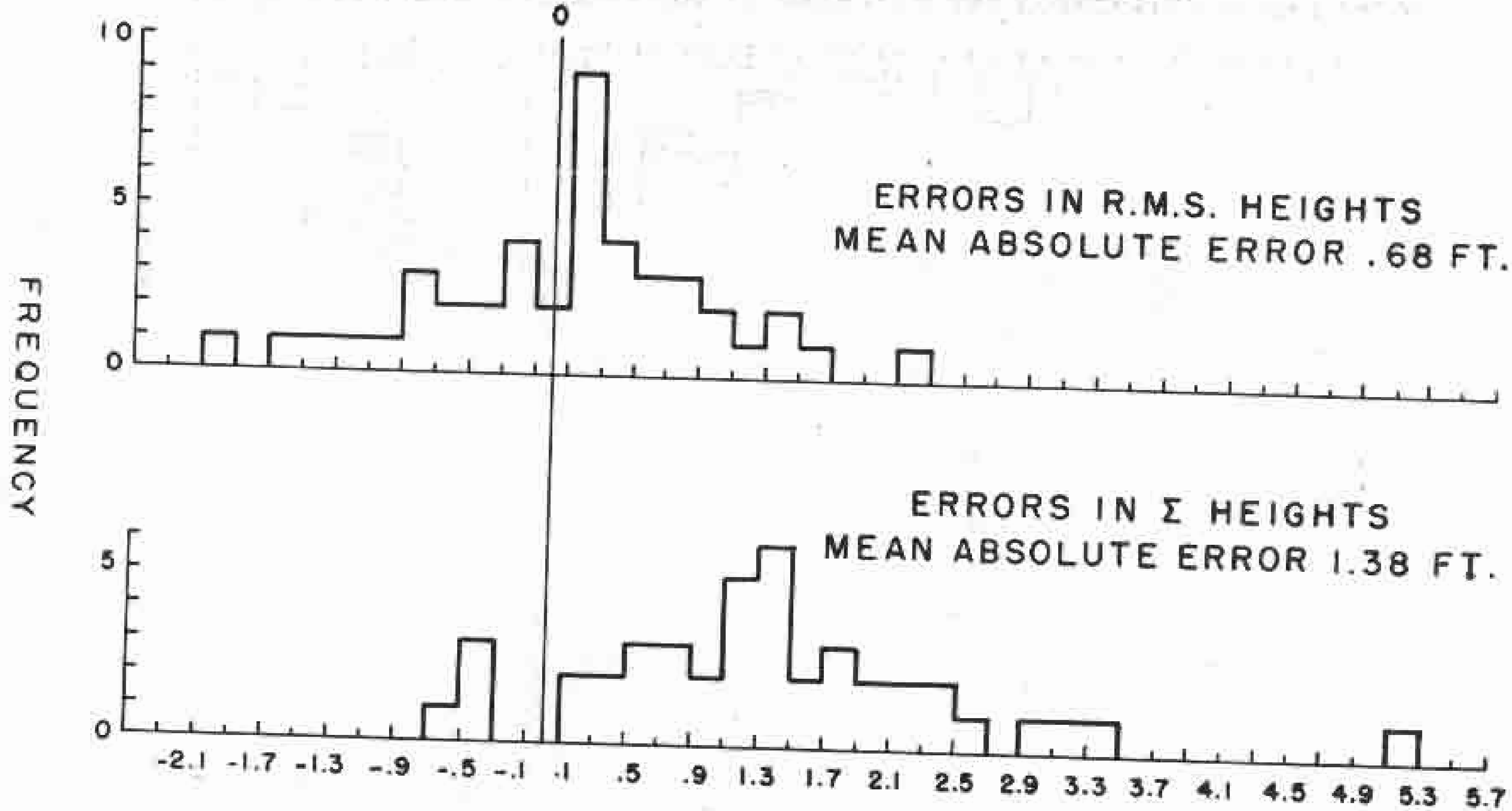


FIG. 19

ACCURACY OF RMS VERSUS Σ HEIGHT FORECASTS

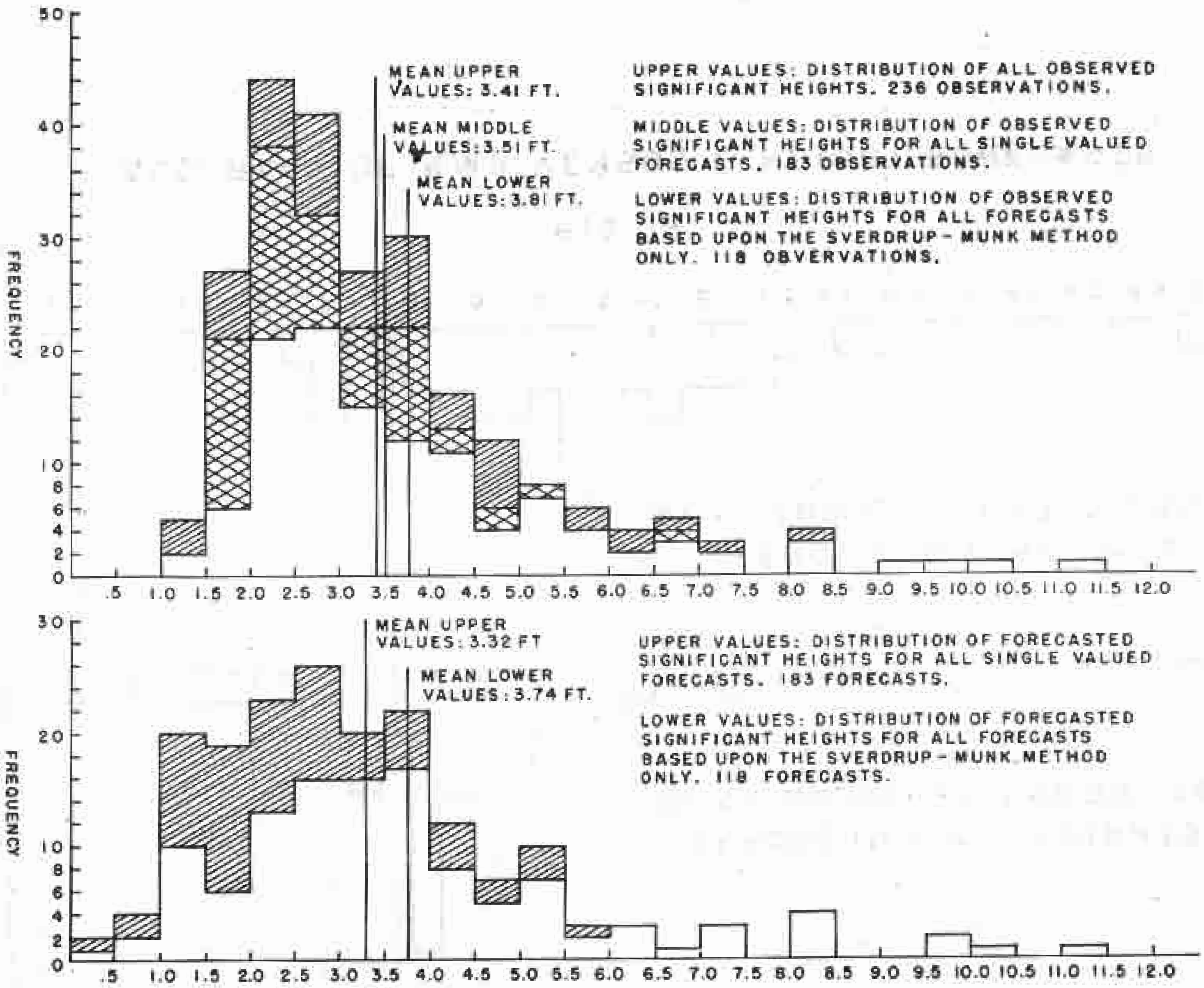


FIG. 20 FREQUENCY DISTRIBUTION OF OBSERVED AND FORECASTED HEIGHT VALUES

height distribution of all 236 observations made during the period of study. The curve is skewed with a maximum at 2.25 feet and falls off gradually toward higher values and sharply toward lower values. The mean significant height of all waves was about 3.4 feet. The mean significant height of 3.4 feet indicates that the period studied was stormier than usual for the east coast. Data presented by Hall (9) indicates that the mean wave height for Long Branch for a year is of the order of 1.9 feet. The fact that the study was made during stormier weather is of course an advantage because it gives better defined situations for analysis. The frequency distribution of the heights reported by Hall was the same general shape as the frequency distribution given here, and there were more low waves reported.

The middle values of the histogram at the top give the height distribution of the 183 observations for which single valued wave forecasts were obtained. There were 44 multiple forecasts and 9 cases in which no forecasts were made. This histogram is essentially the same as the upper histogram and the 183 observations are a fair sample of the total of 232 observations.

The upper histogram of the bottom two in Figure 20 gives the distribution of the 183 forecasted single valued significant heights. The mean forecasted height was about 3.3 feet. This slight difference between the observed and forecasted mean can be accounted for by noting that the distribution of the forecasted values has chopped off a number of values at the sharp peak in the observed values from 2.0 to 3.0 feet and filled them in from 0 to 1.5 feet. Reference to Figures 4 through 7 show that the forecasted heights keep on decreasing for low values of the observed wave height whereas the observed wave height usually stays above 1.5 feet. The two distributions for the single valued forecasts agree essentially except for the low values of wave height.

The upper histogram in Figure 21 shows the frequency distribution of the residual height error after the attempt to get the best possible forecast fit in all single valued forecasts. A few misses greater than one foot are in evidence. The mean of the absolute value of the errors was .60 feet. The residual error represents partly those cases in which good agreement just could not be found, and partly an upper bound on the patience of the analyst in attempting to get a better fit in the height forecast. Six tenths of a foot is about 17% of the mean height of the sample, i.e., three and one half feet.

There was a very slight tendency for the single valued forecasts to be too low. The mean algebraic error for all single valued forecasts was -.14 feet. On the whole, if the size of the sample is considered, Figure 21 shows that the errors in height were small and distributed roughly according to the normal error distribution.

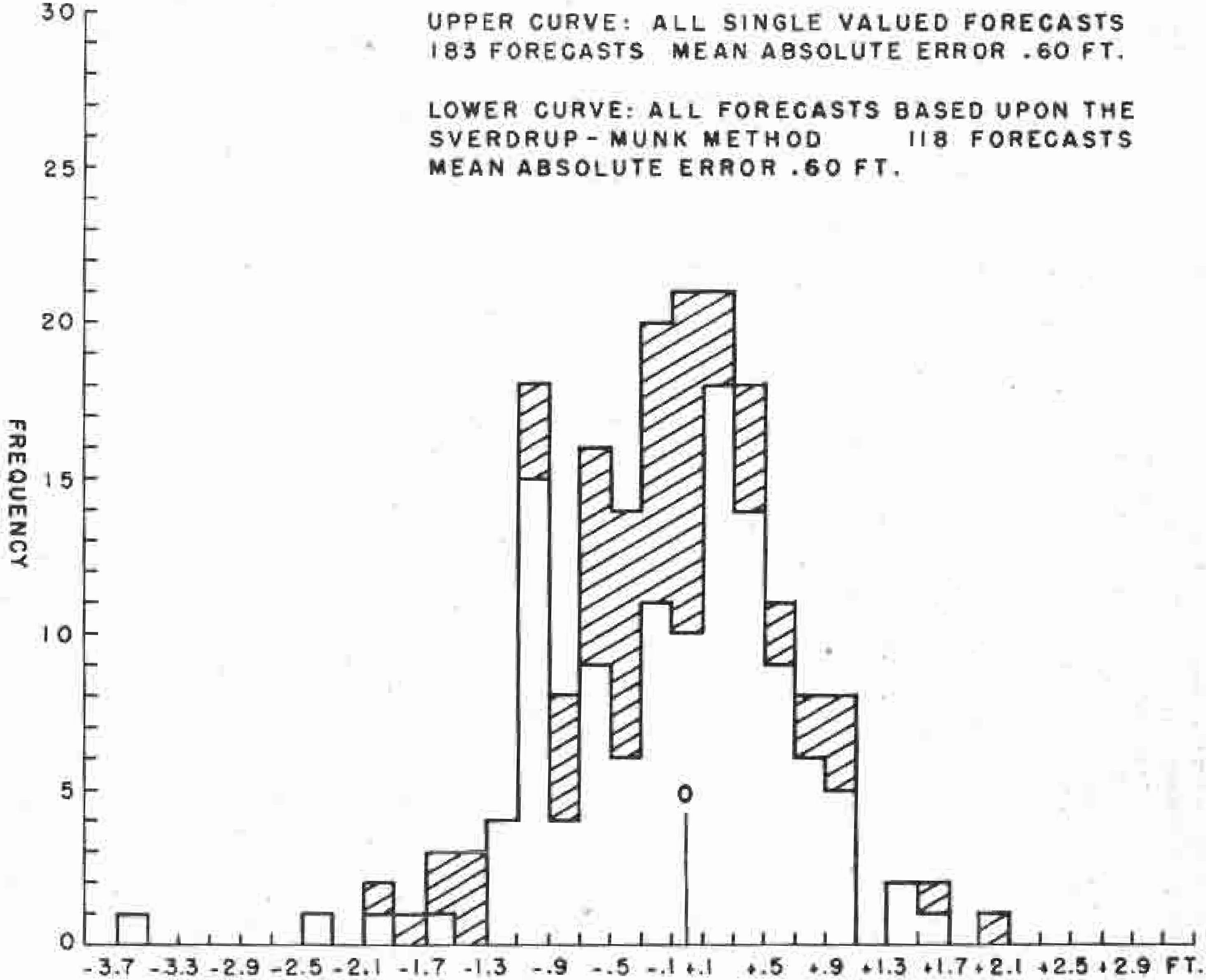


FIG. 21 FREQUENCY DISTRIBUTION OF HEIGHT ERRORS

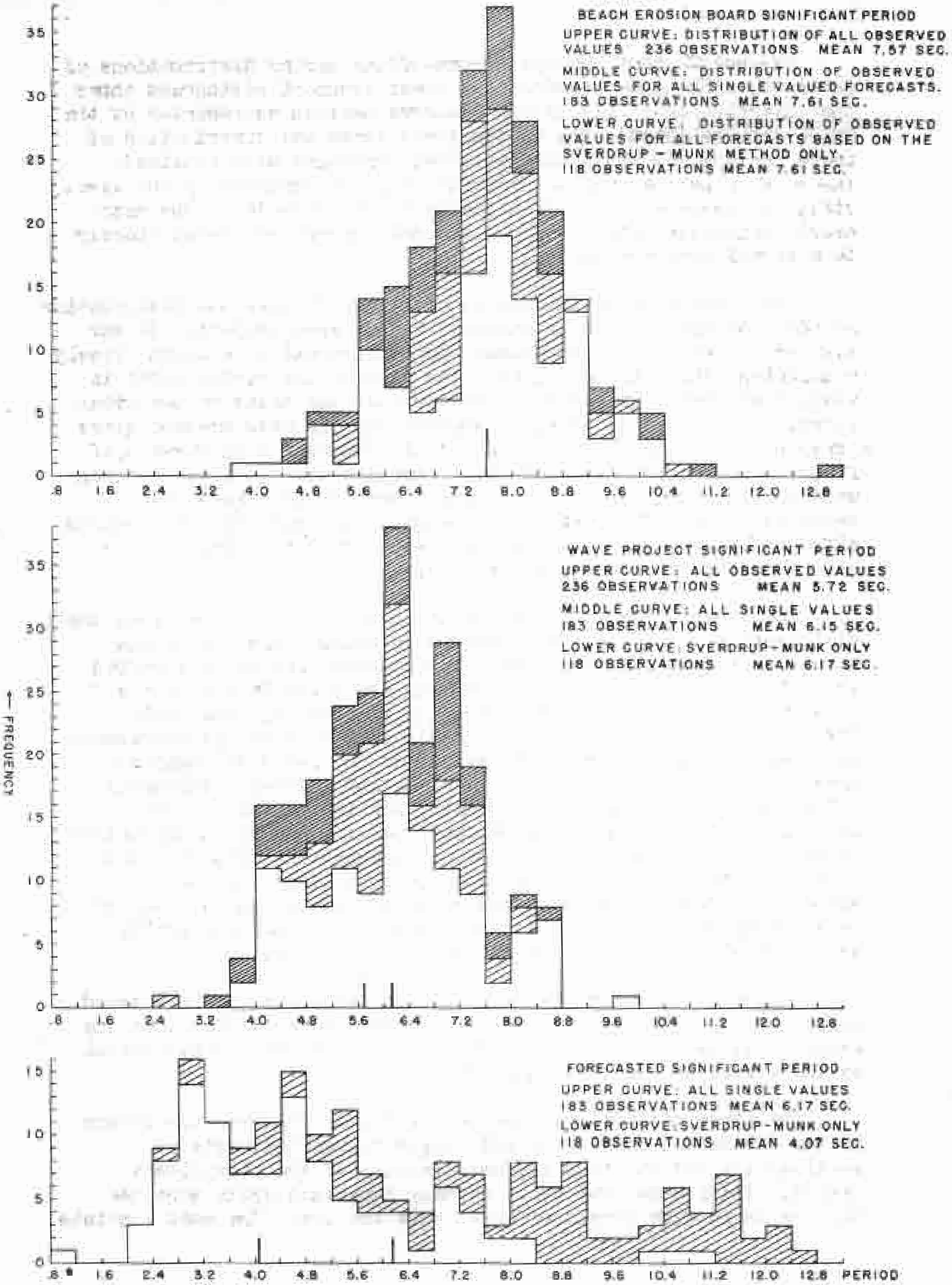


FIG. 22 FREQUENCY DISTRIBUTION OF OBSERVED AND FORECASTED PERIODS

Figure 22 shows the histograms of the period distributions of interest. The upper curve of the upper group of histograms shows the distribution of all of the observed periods as reported by the Beach Erosion Board. The middle curve shows the distribution of those periods for which single valued forecasts were obtained. The mean values of the two distributions are essentially the same, viz., 7.6 seconds. Both distributions are uni-modal. The mean nearly coincides with the mode, and the curves correspond closely to a normal distribution.

The histograms in the center of Figure 22 give the distribution of the observed periods as analyzed by the wave project. If the size of the sample is considered, the distribution is again closely associated with a normal curve. The mean of the middle curve is about four tenths of a second greater than the means of the upper curve. The method of analysis employed by the wave project gives lower periods because intervals such as interval 5 in curve B of Figure 3 were eliminated and only intervals such as 4 and 6 which were well defined for the ten highest most regular waves were employed. The difference is the means of one and one half seconds between the Beach Erosion Board and wave project curves is thus a result of the difference in analysis.

The upper histogram of the histograms at the bottom gives the distribution of all of the forecasted periods for which single valued forecasts were obtained. These values are to be verified against the values whose distributions are shown in the middle curves of the top and center groups of histograms. The most striking thing about this histogram is that it does not correspond in shape even approximately to either of the two distributions shown above. The distribution is wider and flatter. The modal value is at the low end of the scale, and the values are not normally distributed. It is evident that the overall distribution of the forecasted values (both pure Sverdrup-Munk forecasts and decay in fetch forecasts) covers too wide a range and that agreement between forecasted and observed values can be expected only in the region where the forecast graph crosses the graphs of the observed values. (See Figures 4, 5, 6, and 7).

Some statistics on the magnitude of the errors in forecasted periods can now be given. From Figure 22, it is evident that the errors will be large. Figure 23 gives the frequency distribution of the errors in the forecasted periods.

The upper histogram at the top of Figure 23 gives the errors in the forecasted period for all single valued forecasts as verified against the wave project analysis of the significant period. There were just about as many forecasts which were too high as there were forecasts which were too low. The mean absolute

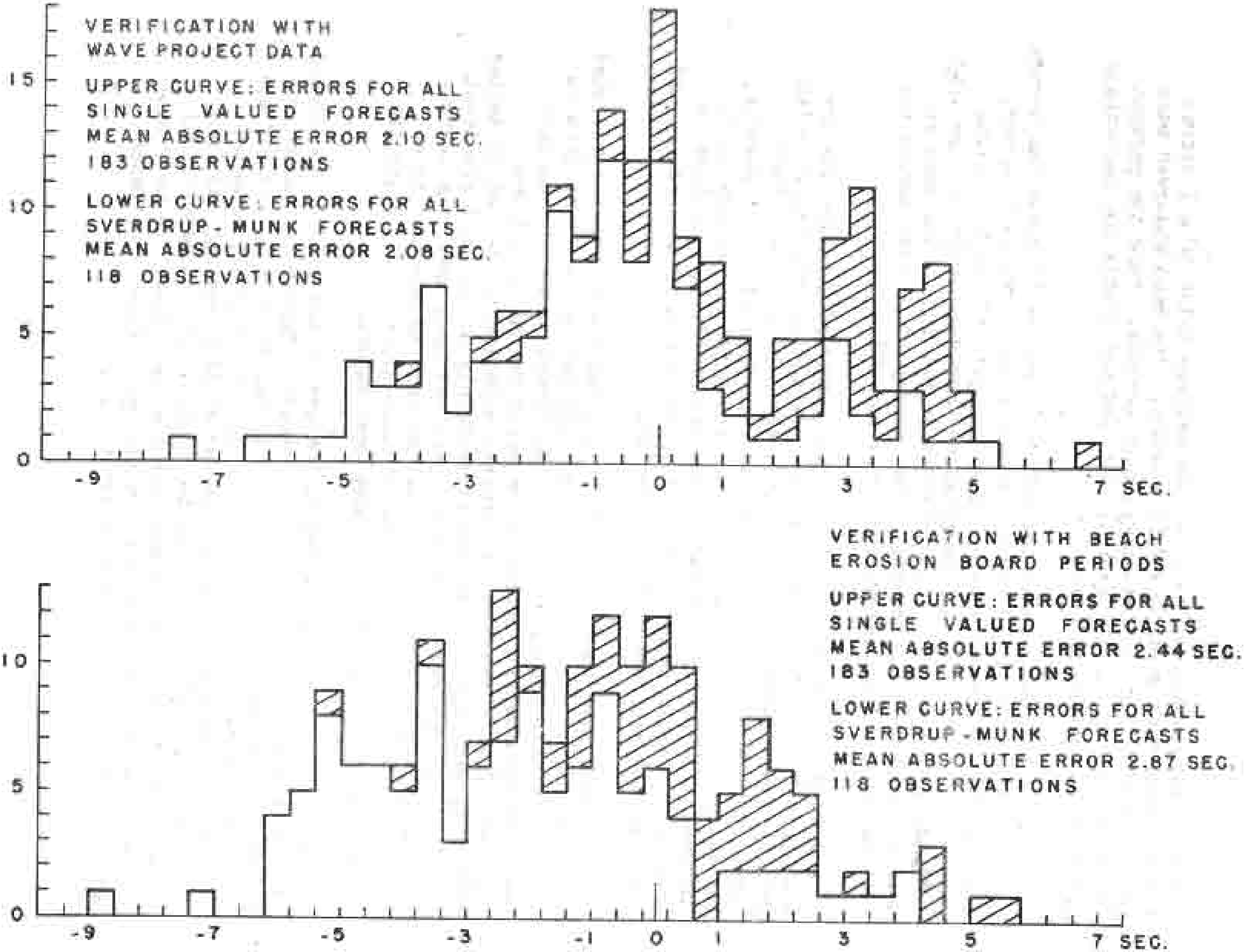


FIG. 23 FREQUENCY DISTRIBUTION OF ERRORS IN FORECASTED PERIODS

error of the forecasts, that is, the average value of all errors without regard to sign, was 2.10 seconds. The mean observed wave project period for the sample was 6.15 seconds. Thus the percentage error was 34% of the mean period and was double the percentage error in the height forecasts.

The upper histogram at the bottom of Figure 23 gives the errors in the forecasted period for all single valued forecasts as verified against the Beach Erosion Board analysis of the significant period. There were more forecasted periods which were too low than there were forecasted periods which were too high. The mean absolute error was 2.44 seconds. The corresponding mean period was 7.61 seconds and the percentage error was 32%.

A very simple way to forecast the observed wave periods for Long Branch would be to forecast the average observed wave period for the time interval studied. In meteorological work, such a forecast would be called a climatological forecast. For example, the mean temperature at Honolulu for the month of January is 71 degrees. Instead of forecasting the day by day termperature at Honolulu it would be possible to forecast the mean temperature and then see how well the forecasts verify.

Suppose then that a period of 7.61 seconds had been forecasted for Long Branch all of the time and verified by the Beach Erosion Data. The mean absolute error in the forecasts would than have been .95 seconds as compared to an error in the techniques employed of 2.44 seconds. A forecast method which cannot do better than a climatological forecast is certainly not of much practical utility. If the wave project analysis had been used, the corresponding values would have been 1.49 seconds as compared to an error in the techniques employed of 2.10 seconds, and again the climatological forecast would have been superior.

Objection might be raised to the use of the mean of the forecast sample for a climatological forecast. Such a procedure is necessary when data is limited, and it had to be employed for the wave project period analyses. Hall (9) has recently reported some statistics for the wave recorder at Long Branch, and from them it is possible to discuss the results of a climatological forecast based upon data other than the test data. Table 9 summarizes the data on periods which can be obtained from Beach Erosion Board Technical Memorandum No. 17.

TABLE 9. STATISTICS ON WAVE PERIODS AT LONG BRANCH (after Hall)

PERIOD IN SEC	4/22/48 to 10/31/48	11/1/48 to 4/30/49	5/1/49 to 10/31/49	4/22/48 to 4/30/49	4/22/48 to 10/31/49
0-2	%	1.9%	%	0.9%	0.5%
2-4	0.1	3.6	1.0	1.7	1.2
4-5	3.4	3.4	4.2	3.4	2.4
5-6	6.6	6.6	23.7	6.7	5.1
6-7	17.8	10.6	38.8	14.4	11.4
7-8	24.9	18.6	20.3	21.9	22.4
8-9	25.3	27.1	10.7	26.2	29.9
9-10	7.9	15.7	1.3	11.5	14.1
10-12	9.7	10.4		10.0	10.3
12-14	4.2	2.0		3.2	2.5
14+	0.1	0.1		0.1	0.1
Mean Period	8.06	7.94	8.68	8.00	8.19

The percentage distribution of the periods in Table 9 shows first of all that the sample studied in detail in this paper is representative of much larger samples, and that all of the periods observed at Long Branch as analyzed by the Beach Erosion Board are grouped closely in an approximately normal distribution about a central mean near 8 seconds.

The mean of the sample employed in this study was 7.60 seconds. If a mean of 8.0 seconds is used to verify a climatological forecast for all single valued wave forecasts at Long Branch, the mean absolute error which results is .99 seconds. If a mean of 8.8 seconds (which is not too representative because the time interval covers the summer months only) is used, the mean absolute error is 1.38 seconds. Thus a climatological forecast based upon samples which do not include the dates of this study would still be superior to the present wave forecasting methods.

Forecasts based upon Sverdrup-Munk method only. The forecasts which will now be discussed were based only on those weather situations where the Sverdrup-Munk method applied. The modifications introduced by Arthur (1, 2) such as the concept of waves coming out of the fetch at an angle were also employed. All cases where the decay in fetch method was used were eliminated.

Figures 20, 21, 22, and 23 can now be restudied for the 118 cases in which forecasts based upon the present accepted theory of wave forecasting were made. All of the unshaded histograms in these figures show data which are applicable to these forecasts.

Figure 20 shows that the distribution of the observed heights for the sample is close to the total distribution of all observations except possibly that a slightly greater porportion of low height observations have been removed. The distribution of the forecasted heights shows that a slightly greater proportion of the low forecasted heights has been removed.

Figure 21 shows that the distribution of the height errors in the smaller sample is essentially the same as the distribution of the height errors in the larger sample. The mean absolute error in the heights is still .60 feet which shows that the percentage height error is slightly smaller because the mean height of the sample is 3.81 feet. However, there is still some residual error in the sample.

The histograms of the observed values of the period in Figure 22 for sample of 118 observations show that the observations which are to verify the Sverdrup-Munk forecasts are not so obviously normally distributed as the total sample. The means of the 118 observations correspond closely to the means of the 183 observations which were used to verify the single valued forecasts.

The histogram of the forecasted values of the period at the bottom of Figure 22, for those cases in which the Sverdrup-Munk method only was employed, is markedly different from the histogram for all single valued forecasts. Many of the high period forecasts have been eliminated and only a few of the low period forecasts have been eliminated. The mean of the sample is 4.07 seconds as compared to the mean of all single valued forecasts of 6.17 seconds.

Figure 23 shows the period forecasts as verified against the wave project periods. There is a definite tendency to forecast periods which are too low. The mean absolute error in the forecast periods is 2.08 seconds. If the period forecasts are verified against the Beach Erosion Board periods there is definite evidence that the forecast periods are too low. The mean absolute error is 2.87 seconds.

Those forecasts which are based solely on the generally accepted theories for forecasting ocean waves can now be tested against a climatological forecast. If the forecasts are verified by the wave project significant period analysis, and if a forecast of 6.17 seconds is made for all forecasts, a mean absolute error of 1.07 seconds is found. Again a climatological forecast which is superior to the forecasting method is obtained.

If the forecasts are verified by the Beach Erosion Board significant period analysis and if a forecast of 7.61 seconds is made for all forecasts, a mean absolute error of 1.00 seconds is obtained. Again, the climatological forecast is superior to the forecasting method.

The Decay in Fetch Method. Figures 20, 21, 22, and 23 show that the decay in fetch method is not much good either. The forecast periods are too high; the distribution of the observed periods does not correspond to the distribution of the forecast periods. Figures 4, 5, 6, and 7 show that there is no tendency for the continued increase in the period as required by the forecasting method.

Table 10 summarizes the statistical data which has been presented in this section.

Some additional interesting information can be obtained by considering the distribution of the differences with regard to sign between the Beach Erosion Board periods and the Wave Project periods. Figure 24 shows the histograms of this difference for those periods associated with the single valued forecasts and the Sverdrup-Munk forecasts. It is easy to see from the wave records which accompany this paper that such a difference can easily arise and that the Beach Erosion Board periods will usually be greater than the Wave Project periods. It is felt that the Beach Erosion Board analysis more closely approximates what would usually be considered to be the significant period because the irregularities in most wave records are smoothed either by the recording instrument or by the analyst.

The Wave Project re-analysis of the data was undertaken in the hope that better agreement between the forecasted and observed periods would result. The slight improvement which was obtained still does not give better results than a simple climatological forecast.

Donn (6) and Isaacs and Saville (10) have reported that the forecasts of the period according to the Sverdrup-Munk method are not too accurate. Donn also reports that height forecasts in some cases are quite uncertain. No quantitative estimates of the magnitude of the errors in the forecasted periods are given.

Donn (6) gives examples of local storms in which it would be necessary to have extremely high winds in order to forecast the observed period. He also illustrates a study of waves from a tropical storm with wave spectra which show a decreasing significant period.

Isaacs and Saville (10) report a mean absolute error in height of less than one foot for actual forecasts. They also state that, "the forecast of wave period ... does not display the same degree of reliability...."

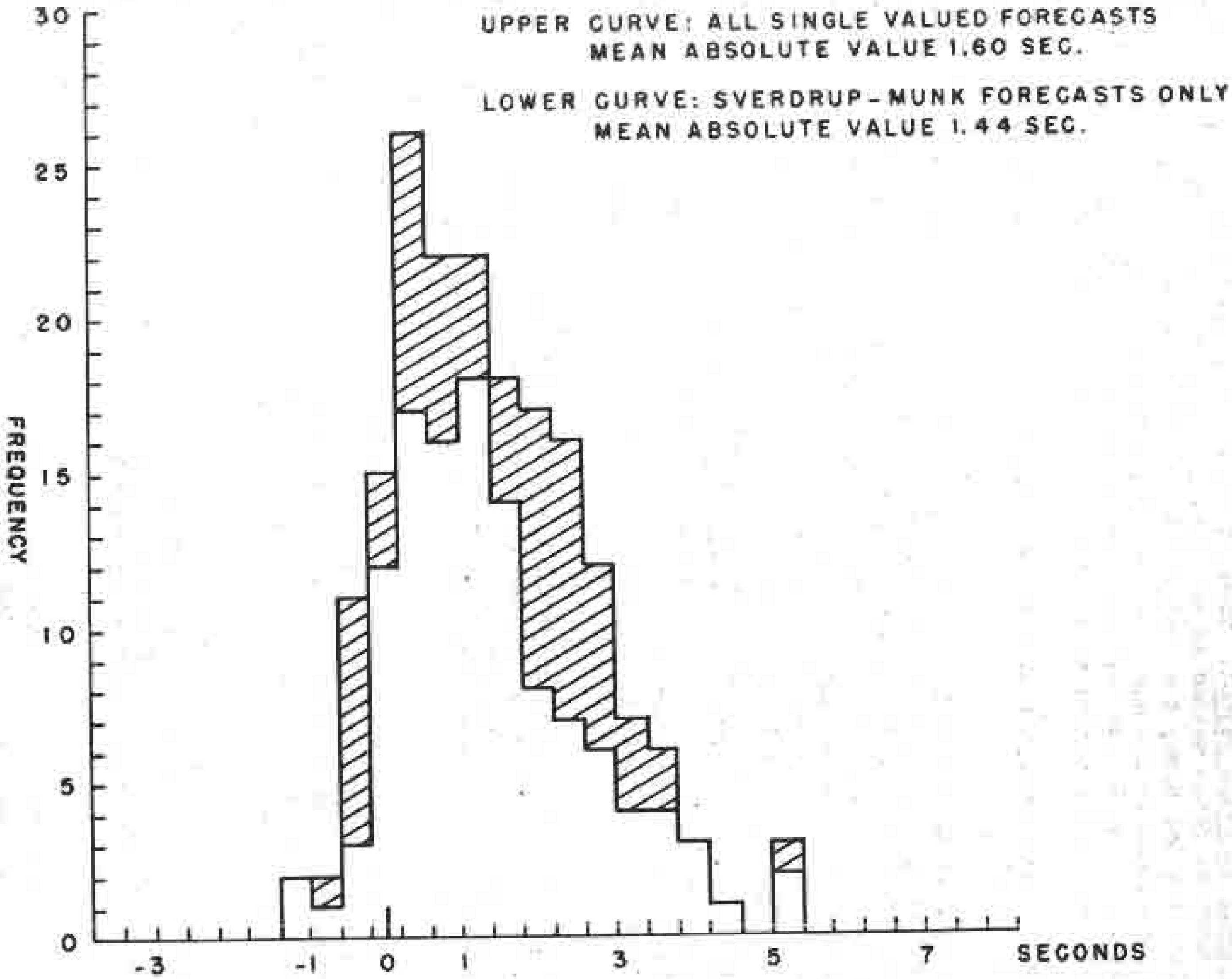


FIG. 24 FREQUENCY DISTRIBUTION OF OBSERVED BEACH EROSION BOARD SIGNIFICANT PERIOD MINUS THE OBSERVED WAVE PROJECT PERIOD

TABLE 10. SUMMARY OF STATISTICAL DATA

RMS Heights versus Σ Heights	
Mean Absolute Error RMS Heights	.68 feet
Mean Absolute Error Σ Heights	1.38 feet
Mean Observed and Forecasted Significant Heights	
All Observations	3.41 feet
Observations for Single Valued Forecasts	3.51 feet
Observations for Sverdrup-Munk Forecasts	3.81 feet
Single Valued Forecasts	3.32 feet
Sverdrup-Munk Forecasts	3.74 feet
Mean Absolute Error in Forecasted Significant Heights	
Single Valued Forecasts	.60 feet
Sverdrup-Munk Forecasts	.60 feet
Mean Observed and Forecasted Significant Periods	
All B.E.B. Observed Periods	7.57 sec.
BEB Periods for Single Valued Forecasts	7.61 sec.
BEB Periods for Sverdrup-Munk Forecasts	7.61 sec.
All Wave Project Observed Periods	5.72 sec.
Wave Project Periods for Single Valued Forecasts	6.15 sec.
Wave Project Periods for Sverdrup-Munk Forecasts	6.17 sec.
Single Valued Forecasts	6.17 sec.
Sverdrup-Munk Forecasts	4.07 sec.
Mean Absolute Error in Forecasted Significant Periods	
Single Valued Forecasts Verified by BEB Periods	2.44 sec.
Climatological Forecast for Above	.95 sec.
Climatological Forecast for Above Based on Annual Mean Significant Wave Period of 8.0 seconds	.99 sec.
Sverdrup-Munk Forecasts Verified by BEB Periods	2.87 sec.
Climatological Forecast for Above	1.00 sec.
Single Valued Forecasts Verified by Wave Project Periods	2.10 sec.
Climatological Forecast for Above	1.49 sec.
Sverdrup-Munk Forecasts Verified by Wave Project Periods	2.08 sec.
Climatological Forecast for Above	1.07 sec.

Section 8 - Attempted Verification of the Refraction Diagram for Long Branch

In order to verify a refraction diagram for one particular point on a coast, the deep water wave height and period, the deep water wave direction, and the wave height, period, and direction after refraction should all be accurately known. The heights and periods of the significant waves after refraction (possible loss of energy due to bottom friction, and diffraction) are the only observed values. The data are simply not sufficient for a precise verification.

It is noted in passing that Sverdrup and Munk make the following statement in Wind Sea and Swell; Theory of Relations for Forecasting. "Therefore, the growth and decay of significant waves do not obey the laws that would apply to the waves of classical theory..." The statement might be amended to read, Therefore the growth, decay, refraction and diffraction of significant waves do not obey the laws that would apply to the waves of classical theory. The theory of wave diffraction and refraction as employed in practice is based upon classical waves of constant height and period, and there is considerable doubt that one value for the significant height, one value for the significant period, and one value for the deep water wave direction adequately characterize the sea surface.

In the test forecasts described previously, the waves were refracted with the forecasted period. The height after refraction was verified against the observed height value, and an attempt was made to obtain the best agreement possible. It has been shown that the forecasted period was in error frequently by more than two seconds. An error of plus or minus two seconds can result in huge percentage errors in the height forecasts as shown by Figure 1 if the value for the period is critical. In this section, an attempt will be made to discover how the errors in the period affect the errors in the height which enter because of the use of the refraction diagram.

The forecasted period and the forecasted height are inextricably connected in the forecast method. If, despite this fact, the wave height at the instrument is computed from the refraction diagram by using the forecasted deep water significant wave height and the observed significant wave period at the instrument, it is possible to obtain an estimate of the effects of refraction upon the accuracy of the forecast heights.

Figure 25 shows the histograms of the errors in height which result if the waves are refracted by the observed period instead of the forecasted period compared to the errors which resulted by refracting the waves with the forecast periods and compared to the errors which would have resulted if the deep water wave height

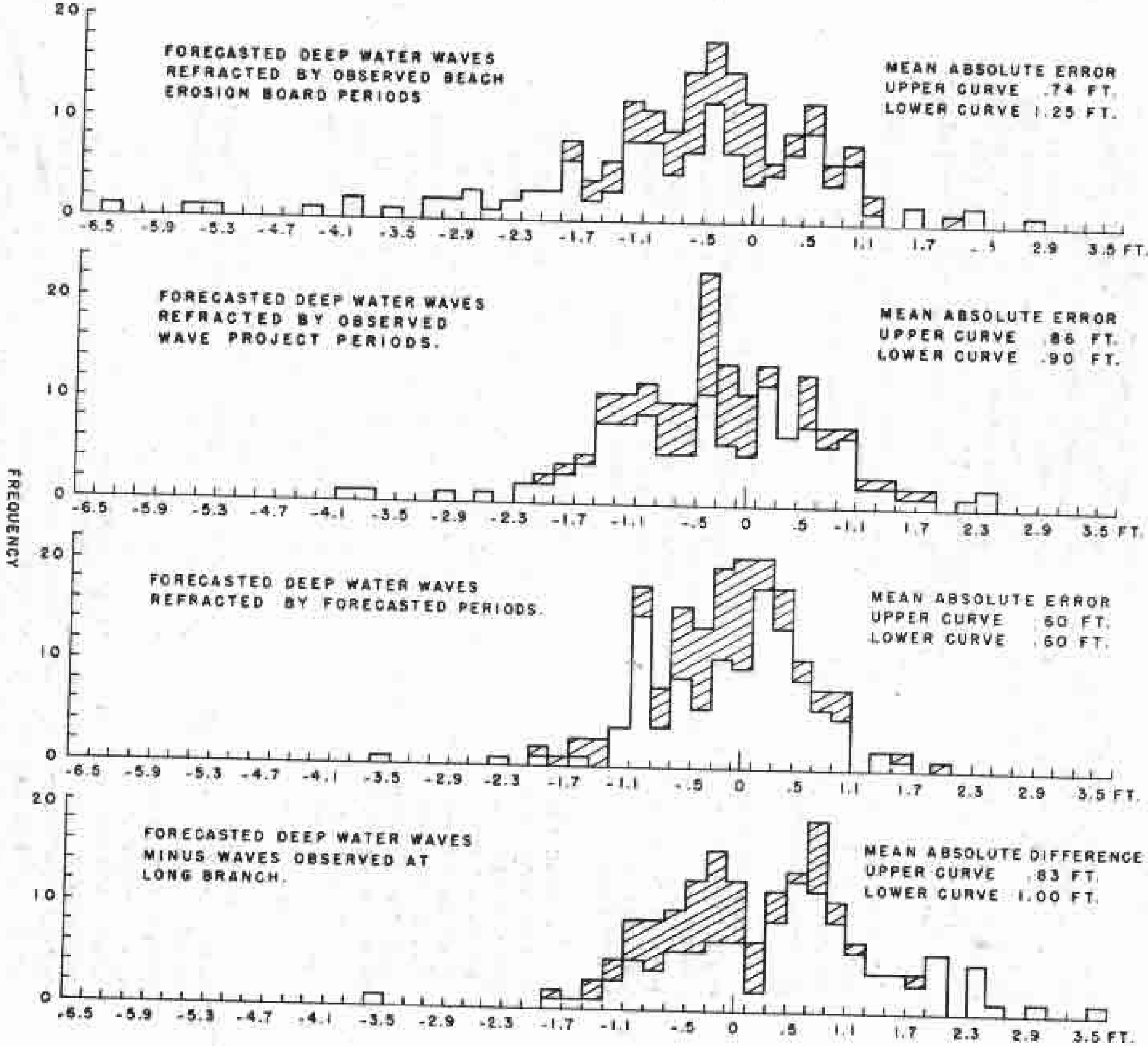


FIG. 25 ATTEMPTED VERIFICATION OF REFRACTION DIAGRAM

had been forecasted to be the height at the instrument. The third histogram from the top in Figure 25 is a copy of Figure 21 for comparison.

The top histogram in Figure 25 show the errors which result if the forecasted deep water waves are refracted by the observed Beach Erosion Board Periods. It is to be expected that this pair of histograms would have a greater dispersion than the third pair of histograms because the third pair of histograms gives in a sense the least error possible. The mean absolute error is 50 per cent greater than the original height error minimum for all single valued forecasts and over 100 per cent greater for the Sverdrup-Munk forecasts.

The second pair of histograms gives the corresponding data for refraction by the Wave Project Significant Period. The mean absolute error in both cases is about 50 per cent greater than the original minimum height error.

The bottom pair of histograms gives the height error which would have occurred if the deep water wave height had been forecasted to occur at the instrument; i.e., $K_d D = 1$ for all periods and all directions. The mean absolute error is comparable to the errors reported in the first two pairs of histograms. Waves which were too high would have been forecasted more often.

A mean absolute error of six tenths of a foot is 17 per cent of the mean height of the sample, and so a mean absolute error of one and one quarter feet would be about 36 per cent of the mean height of the sample. Thus the errors in height due to the refraction diagram are of the same order of magnitude percentagewise as the errors in the forecasted period. It must be concluded that the original forecasted deep water values are not adequate enough or accurate enough to verify the refraction diagram. If the percentage errors in height had been double or triple the percentage errors in period, it might have been possible to study the accuracy of the refraction diagram more adequately.

The author is also of the opinion that it would have been possible to obtain mean absolute errors near six tenths of a foot in all three cases by changing the original values of the forecast parameters within the range of possible choices and trying to fit the forecasted heights to the observed heights at the instrument after refraction by the observed periods or after no refraction whatsoever. Or to state it another way, the added refinement of a refraction diagram at Long Branch on an average basis, gives such small corrections to the forecasted heights as compared to the possible errors in the forecasted deep water heights and periods and the possible range of choices in the forecast parameters, that its effect is negligible in improving the forecast.

It should not be concluded from the above statement that the refraction diagram is of no use. If the forecasting method were better, the refraction diagram would then be of great importance.

Section 9 - The Nature and Usefulness of Actual Forecasts Using Present Methods

The usefulness of a forecasting method depends upon what the forecasts are to be used for and upon the effect of an error in the forecasted values on the overall results. Thus the Sverdrup-Munk Method, modified by practical experience, has proved useful in many applications. For example, rescue operations at sea, military operations, offshore oil drilling operations, and engineering projects such as the construction of breakwaters and jetties are all made safer and more economical by forecasts of the wave heights. In these applications, the methods at their present stage of development are adequate.

Forecasts of wave heights over the open ocean under conditions in which the wave period is not important have been made for three years by the United States Coast Guard Search and Rescue Section in New York. A thirty hour general forecast is prepared, and a specific spot forecast for each rescue operation is also prepared. The individual forecasts are verified either as right or wrong. A one foot error for heights up to five feet, a two foot error for heights up to 10 feet, and a three foot error for heights up to fifteen feet, and a four foot error for heights up to twenty feet is permitted. For heights greater than twenty feet a five to six foot error is permitted. The thirty hour forecasts as verified by this method are 85 per cent accurate. The spot forecasts for each rescue operation with a range from two to four hours are 95 per cent accurate.

The usefulness of the forecast method in the oil industry is discussed by Graham and Geyer (8) in connection with the overall application of Meteorology to operational problems. They report that many operations depend almost entirely on favorable sea conditions, and that the wave height forecasts save time and provide additional safety for the operational crews.

The importance of wave forecasts in connection with engineering applications has been discussed by Mason (12). The importance of wave forecasts in invasions has been discussed by Bates (3).

From the above short summary, it is evident that the Sverdrup-Munk wave forecasting method has given and will continue to give important information to many persons connected with the various activities of mankind on the oceans and at the shore. For these applications and others which have not been given such as fishing, small craft warnings, etc., the method is accurate enough to be useful.

However, the method has its limitations. Any wave effect which depends critically on the forecasted period is difficult to forecast and to interpret. It appears also that the more fundamental problems connected with beach erosion and the design of structures cannot be successfully attacked with the present concept of the significant wave and that if possible more refined and more accurate methods of wave record analysis and wave forecasting should be developed.

Section 10 - Application of This Study to Beach Erosion

Although this study has not been thorough enough or accurate enough to give precise quantitative results on problems connected with beach erosion, it is still possible to discuss some important conclusions which can be reached in connection with the qualitative understanding of the processes involved. Wicker (19) has given the basic explanation of the observed littoral drift on the New Jersey coast, and it is possible from this study further to substantiate his explanation and to restate it in what is believed to be a more precise form from a meteorological point of view. It is also possible to discuss the relative protection of various points on the coast from wave attack. The energy associated with the various directions of deep water wave approach can be estimated.

In section 7, it was pointed out that the period studied was stormier than usual and that the mean significant wave height was considerably higher than average. The discussion which follows therefore applies only to the period studied and is not representative of a whole average year. Periods of greater storm activity are of interest in themselves because of the changes they can effect in the shore line.

In addition, the frequency of waves from various directions may not be the same in this study as they are on an average. Deep water waves from due east may be more frequent in this study than usual.

Figure 26 is a schematic representation of New York Harbor and of the Long Island and New Jersey Physiographic Units. It illustrates the point that the Long Island and New Jersey coasts intersect in a corner at the entrance to New York harbor and that the two coastlines are roughly symmetrical upon reflection in the axis of the Hudson canyon.

In section 6, some statistics on local waves and waves from distant fetches were presented. From these statistics and from the statistics on observed wave periods given in section 7, it is possible to give an explanation for the observed littoral drift on the Long Island and New Jersey coasts. It is necessary to

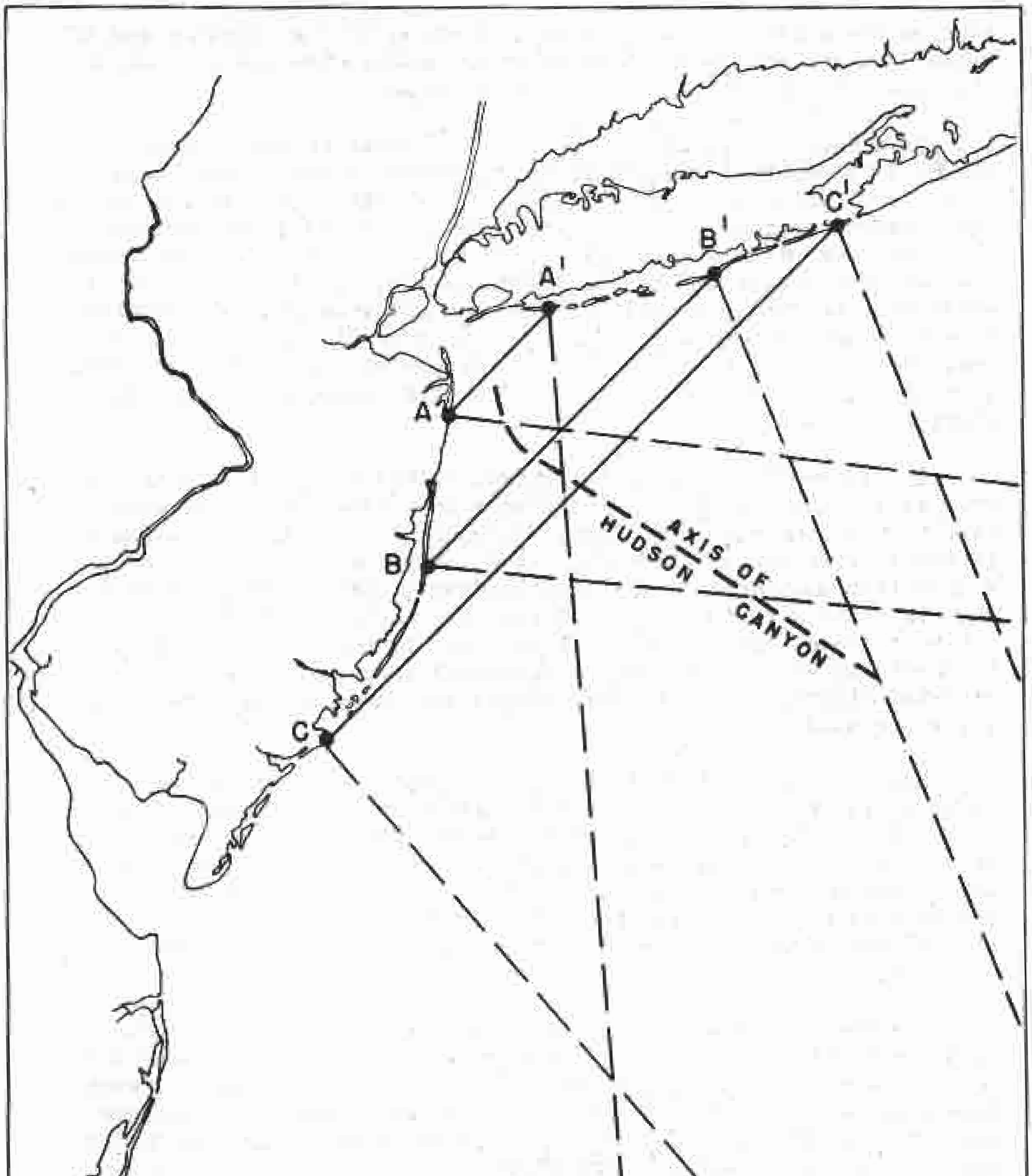


FIG. 26

WAVE ACTION ON THE LONG ISLAND AND NEW JERSEY COASTS discuss the effects of local waves, of waves from a distance and of waves from an east coast storm in order to describe the effects of the waves on the beaches.

Consider, first, the effect of local waves on the coasts. Figure 17 shows that about half of the waves at Long Branch were caused by local winds. In addition, the statistical distribution of the observed periods shows that half of the waves at Long Branch have observed periods less than eight seconds. Therefore the waves are not unduly affected by the Hudson Canyon, and so the effect of refraction is purely a local problem and not a large scale problem. To a good degree of approximation, it is possible to say that the wave breaks at the shore at an angle determined by whether the wave direction is to the left or right of a line perpendicular to the shore at a given point on the coast.

In Figure 26, consider the paired points A, A'; B, B'; and C, C'. At A', any low period wave with a deep water direction eastward of the line running southward through A' will tend to cause a littoral drift toward the west. At A, only low period waves with a direction southward of the line running eastward through A will tend to cause a littoral drift toward the north. Also there is not much ocean left to the north of A and to the west of A' so that the areas in which waves can be generated to cause oppositely directed littoral currents are limited and the possible directions are restricted.

Suppose that northeast winds are blowing over the entire area shown in Figure 26. There are two possible ways to forecast the waves at A. The first would be to use the distance of 25 miles from A to A' as a fetch and forecast deep water waves travelling toward the southwest. The second way would be to assume as Arthur does (1) that northeast winds produce some component significant waves which travel toward the south south west and toward the west.

For the same wind speed, the first forecasting method gives much lower waves at A than at B due to the limitation of the fetch. For the same wind speed, the second forecasting method gives waves traveling more nearly normal to the shore at A than at B, because the distance BB' is longer and it is to be expected that the waves would travel more nearly in the direction of the wind. The waves might be nearly the same height at A and B in the second case. However, in either case, that portion of the wave energy which produces the littoral current is less at A than it is at B. Similar remarks hold true for any wind direction from north through east northeast, and in every case the presence of Long Island suggests that the strength of the littoral current toward the south should increase as the distance from New York Harbor increases.

Points A and A' and B and B' are symmetric, and with obvious changes exactly analogous remarks can be made for A' and B' on Long Island. Points C and C' are not quite as symmetric as the other points because of the curvature of the New Jersey coast south of B. At C, for waves from the northeast, the littoral current should be stronger than at B because of the greater angle of breaking.* If the local winds are low enough so that the fetch is not a limiting factor southwest waves would produce the same littoral current at B' and C', other things being equal.

Local winds from any southerly direction at A and B would produce a northward littoral durrent of nearly the same strength, but at C the waves must be caused by winds from the south of south east before a littoral current toward the north is produced.

In summary then, the waves caused by local winds produce different results along the New Jersey coast. For winds which tend to generate waves which produce southward from A to B to C. Those winds which cause waves which result in northward littoral currents yield the same strength currents at both A and B, and if the current is northward at all, a weaker current at C. Finally, as pointed out by Wicker (19), if the wind distribution is the same at all three points with respect to direction, the littoral current will be southerly more often at C than at A and B.

Now consider the effect of waves from a distant fetch on the points shown in Figure 26. Distant fetches account for the other half of the waves observed at Long Branch (point A). Few of the observed significant periods were greater than ten seconds, but Figure 1 shows that they would be somewhat affected by the large scale refraction features. Figure 16 shows that only one of the seventeen distant fetches which were located during the period of the study could have produced a littoral current toward the south at Long Branch. Many distant fetches which might have caused southward littoral currents seem to have been neutralized by the application of Arthur's theory. Several could have produced northward littoral currents.

The situation is decidedly different in one important aspect at points B and C. Those distant fetches with generating areas running northeastward from just east of Cape Cod and which cause waves at Long Branch from nearly due east can cause waves at points B and C from the east north east and north east. These waves would produce a southward littoral current.

All of the reported distant fetches would have produced westward littoral currents on Long Island. The area to the westward

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* The assumption that the decrease in wave energy due to refraction does not offset the effect of a greater breaking angle is made.

of the lines running southward from A', B', and C is the only source region for distant waves which could cause eastward littoral currents. This area is not a source region of very many high waves because strong winds are not frequent.

East coast storms are probably the most important single cause of erosion on the New Jersey and Long Island coasts. Atlantic storms at distances greater than one thousand nautical miles from the coast are probably secondary in importance. Tropical hurricanes at distances greater than six hundred nautical miles from the coast may have some effect, but as hurricanes move northward they assume extra tropical characteristics and, if near enough to the coast, they can be classified with the east coast storms.

Miller (13) has made a study of cyclogenesis in the Atlantic coastal region of the United States. From this study, it is possible to describe some of the average properties of east coast storms. There were two hundred and eight east coast storms during the period of his study from 1929 to 1939. Eighty-six storms, classified at type A, were formed as meteorological waves on a cold front, and one hundred twenty-two, classified as type B, were formed in advance of an occlusion as the example shown in Figure 9 for May 5, 0130 EST. Of the total number of storms studied, the data presented by Miller show that approximately seventy-five per cent of the storms formed at a location such that their future paths would sweep from south to north along a track toward the northeast, which would pass to the east of the New Jersey-Long Island coasts. The tract of the low center of the storm studied in Figure 9 is typical of a very larger percentage of type B storms, and the point of origin of the storm is almost exactly at the point of maximum frequency of cyclogenesis for such storms. The most frequent area of origin of type A storms is about one hundred fifty nautical miles south south west of Cape Hatteras.

Fortunately, then, the storm studied in detail in Section 6, Figure 9, is a typical example of an east coast storm and its effects on the beaches would be representative of the effects of many such storms. This storm will therefore be discussed in connection with the littoral currents which it might have produced at points A, A', B, B', and C, C' in Figure 26.

At the start of the build up of the waves from the storm, the waves were from the southeast and build up to a height of four feet in six hours as shown by the May 5, 0130 map and by Table 7. The wave direction is representative for all points along the coast. Weak northward littoral currents were therefore to be expected at A and B. There should have been practically no current at C. A', B', and C' should have had westward littoral currents.

During the next eight hours, the waves were probably from the east south east at A, B, A', B', and C', but the May 5, 0730 map shows that the winds and therefore the waves were from due east near point C. The waves built up to a height of seven feet at Long Branch (A); and they were probably four or five feet higher at C. The littoral currents would have been northward at A and B, westward at A', B', and C', and southward at C. Note that the position of the points with respect to the storm center is important when the storm is at the coast.

For the next seven and one half hours the waves were probably from due east at A, B, A', B' and C'. The curvature of the isobars around the low center, the coastal winds, and the fact that the dominant fetch is to the north of C, all suggest that the waves at C had a northerly component. The littoral current at A and B was probably small (although the waves are about twelve feet high), because the waves were nearly normal to the coast. The current was westward at A', B' and C' and probably quite strong. At C, the current was southerly.

The sharp drop in wave height after 2000 May 5 as shown in Figure 5 is difficult to explain by present forecasting techniques. After May 6, 0130 the situation is better defined and the waves can be forecasted more easily. The May 6, 0130, 0730, and 1330 maps all show a generating area to the east of Cape Cod. In addition, the generating area is to the north of the New Jersey coast. The east and northeast winds over the generating area combined with the sheltering effect of Long Island and the concept of waves coming out of the fetch at an angle, show that the angle of the breaking waves with the coast at A should have been less than the angle of the breaking wave with the coast at B. In turn, the angle of the breaking wave with the coast at B should have been less than at C. The waves were probably slightly lower at C than at A but the deep water wave direction compared to the normal to the coast at the point varies through almost 90°. Thus the strength of the southward littoral current should have increased toward the south from A to B to C. The littoral current was westward at A', B', and C'.

Table 11. Probable Direction and Estimated Intensity of the Littoral Current at Six Points on the New Jersey and Long Island Coasts During the Passage of an East Coast Storm.

From	To	A	B	C	A'	B'	C'
May 4 2000	May 5 0200	North Weak	North Weak	Neutral	West Weak	West Weak	West Weak
May 5 0200	May 5 1200	North Moderate	North Moderate	South Moderate	West Moderate	West Moderate	West Moderate
May 5 1200	May 5 1930	Neutral	Neutral	South Moderate	West Strong	West Strong	West Strong
May 5 1930	May 5 0130	Neutral(?)	South(?) Weak	South Moderate	West Moderate	West Moderate	West Moderate

May 6 0130	May 6 1330	Neutral(?) Weak(South)	South Weak	South Moderate	West Weak	West Weak	West Weak
Dominant Current		North	North (Neutral)	South	West	West	West

Table 11 summarizes the directions toward which the littoral current was probably flowing for convenient time intervals during the passage of the storm. A crude estimate of the strength of the littoral current is included. At the present state of knowledge concerning the effect of waves on the beaches, it is not possible to give actual values of the currents, nor is it possible to compute the quantity of sand moved by this one east coast storm.

It is possible from the forecast data to decide upon the deep water wave direction to within sixteen points of the compass. If the waves were classical waves, the square of the wave height would be proportional to the potential energy per unit area of the sea surface. Since the waves are significant waves, the square of the significant heights is an over estimate of the wave energy and may be in error as shown in Section 3. On the other hand, in Section 6 the significant waves for multiple valued forecasts combined as if the wave heights were closely related to the wave energy, and the error may not be too great on an average basis.

The deep water wave direction was known from the forecast data. The forecasted deep water wave height before refraction was also known. The wave heights as forecasted for four-hour intervals were tabulated according to direction within the accuracy of the weather data to the nearest sixteen points of the compass. Each deep water wave height was squared and the sum of all the squares for a given direction was computed. Figure 27 shows the percentage of total wave energy which traveled toward Long Branch along each reported direction. About 24 per cent of the wave energy is approximately neutral. 33.4 per cent would produce southward littoral currents and 42.6 per cent would produce northward littoral currents.

Figure 27 does not represent energy flux toward the coast. If the waves were classical waves, each height could have been weighted by the wave period and the energy flux in deep water would have been proportional to H^2T, but since such considerations have not been shown to apply to significant waves, such a computation was not made. Figure 27 does however, suggest that the net littoral current was northward at Long Branch during the period of study.

All of the data presented in this section substantiated the conclusions and observations which have been presented by Wicker(19). Wicker makes the following points in the above reference which are

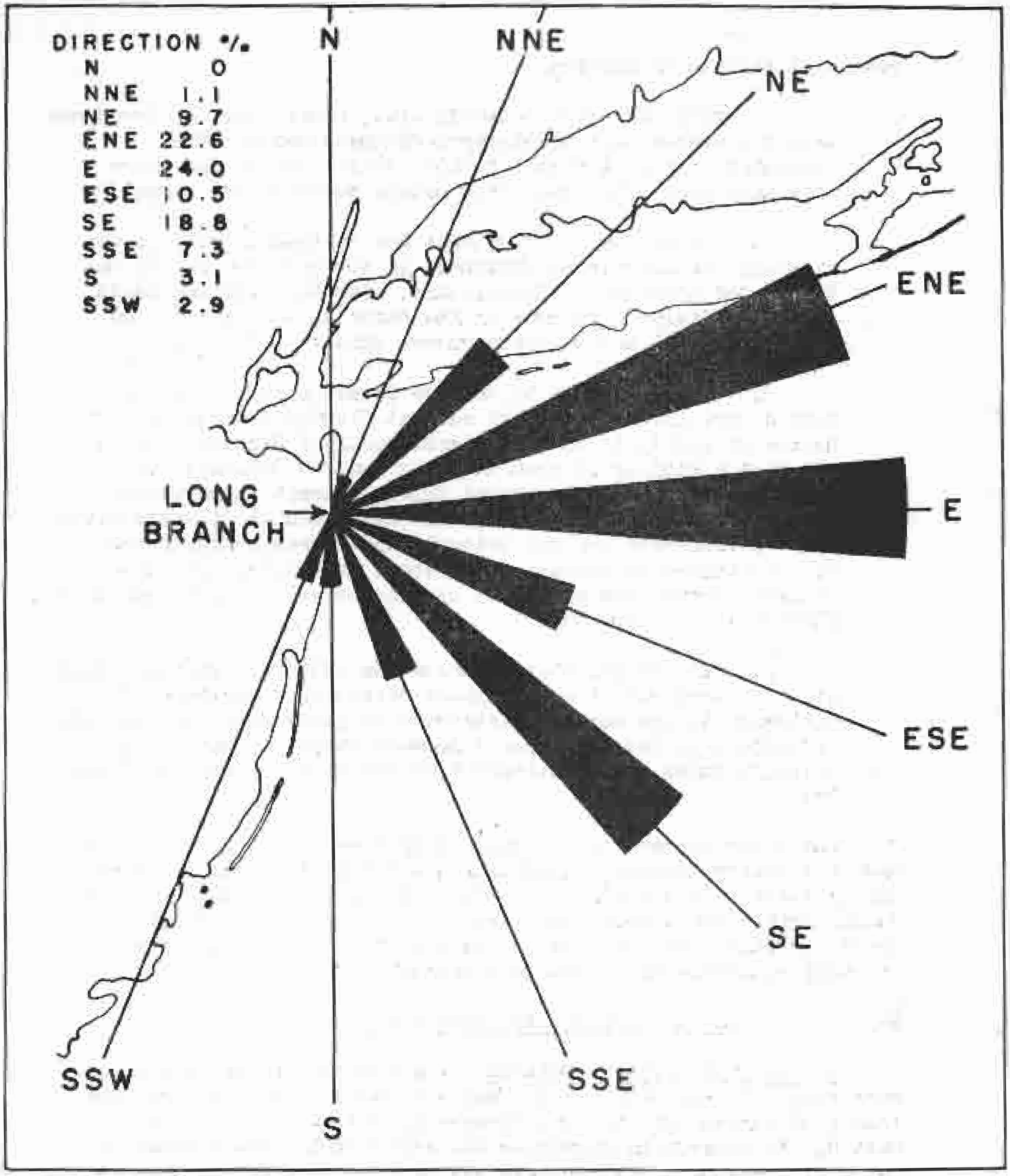

FIG. 27

PERCENTAGE OF TOTAL ENERGY IN DEEP WATER FOR VARIOUS WAVE DIRECTIONS pertinent to this discussion.

1. "The data--(on Atlantic City, Ocean City, Wildwood and Cape May)--show that waves approach these beaches from directions north of normal to the general set of the shore line much more often than from points south of the normal."

2. "It may be inferred that the northeast swell is considerably reduced in significance in Northern New Jersey due to the lee provided by Long Island, also that the southeast swell is likely to impinge on the beach at an angle to the south of normal to the northern New Jersey shore line."

3. "Applying this to the New Jersey coast, it is seen that a wave induced littoral current flowing towards New York Harbor is likely to be encountered north of Barnegat Inlet, and that a similar current settling towards Delaware Bay should exist south of Barnegat Inlet. Direct observations covering a considerable period are available at Atlantic City, where a recording current velocity and direction apparatus was maintained in operation for about two years. The data obtained showed the existence of a non-tidal current generally flowing toward Cape May."

4. "The forces that generate the littoral drift are such that its predominant or resultant direction of movement is northward to the northern extremity of Sandy Hook from an area (sometimes called the 'node') between Manasquan River and Barnegat Inlet, and southward from the node to the tip of Cape May."

One final comment on the overall problem of beach erosion is that the theory is purely qualitative and that it needs to be made quantitative. In the opinion of the author, the concepts of significant height and significant period are not accurate enough to permit quantitative results on the energy flow with the waves refraction, diffraction, and sand transport.

Section 11. <u>Conclusions and Recommendations</u>

<u>Accuracy of Forecast Methods</u>: The forecast techniques which were employed were designed to test the Sverdrup-Munk theory, the theory of variability in wave direction, and the decay in fetch method. An attempt to eliminate the errors which would enter because of inadequate weather data was made by fitting the observed heights to the forecasted heights as accurately as possible.

There were a number of situations in which multiple waves were forecast. Statistically the square root of the sum of the squares of the significant heights is more accurate than the sum of the significant heights as a forecast of the observed significant heights.

The Sverdrup-Munk method, either combined with or separated from the decay in fetch method, does not verify with respect to forecasted significant periods. Greater accuracy is obtained by forecasting the mean annual observed significant period. It follows that the decay in fetch method will not verify with respect to forecasted significant periods either.

The concept of the variability in direction of wave travel as developed by Arthur was most helpful in explaining the observed wave heights. The forecasting graph which was presented resulted in such small percentage changes in the forecasted significant wave periods for the range of values which occurred, that no attempt was made to verify its accuracy by separating those forecasts which depended on the method from those forecasts which did not depend on the method. The error in the overall method is so great that whatever accuracy this graph may have is probably completely masked.

Actual test forecasts for Long Branch without foreknowledge of the actual significant wave heights and significant wave periods are being completed. From them, it will be possible to discuss the errors in the forecasted height.

An attempt to verify the refraction diagram presented in the previous report was made. The errors in the forecasted significant period cause errors in the significant heights after refraction of the same percentage order of magnitude as the errors in the forecasted significant periods. Therefore, the refraction diagram could not be verified. The attempt to verify the refraction diagram with only forecasted significant values in deep water might be compared to an attempt to measure the diameter of a dime with an uncalibrated yardstick.

Usefulness of the Forecast Methods: The forecast methods studied herein are useful in many applications. However, any situation which depends critically upon accurate wave periods cannot be adequately forecasted. The successful solution of more intricate problems connected with ocean waves (such as beach erosion) in the opinion of the author must await better methods. Hindcasts based upon the methods for the purpose of collecting statistical data for a given beach may not be accurate enough or detailed enough to warrant the effort.

Applications to Beach Erosion: The large scale features of the littoral currents on the New Jersey coast and the Long Island coast have been explained qualitatively. The waves from an east coast storm seem to be the most important single factor in the study of erosion in the area considered.

Recommendations. The results of this study in the opinion of the author make it evident that better methods of wave analysis which will eliminate the concepts of significant period and significant height are needed. Better observations at more points on the New Jersey and Long Island coasts and in deep water will yield more reliable data than hindcasts. Numbers which stand for something precise are desparately needed.

Section 12. Acknowledgments

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